CESAR Science Case

The Colours of Astronomy

Observing the visible and invisible Universe

Teacher Guide

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Fast Facts

FAST FACTS

Age range: 14-18

Type: Guided investigation

Complexity: Medium

Teacher preparation time: 1 hour

Lesson time required: 1 hour 15 minutes

Location: Indoors

Includes use of: Computers, internet

Curriculum relevance

General

- Working scientifically.
- Use of ICT.

Physics

- Waves.
- Light waves. The electromagnetic spectrum.
- Temperature. Blackbody radiation.

Space/Astronomy

- Research and exploration of the Universe.
- The evolution of stars.
- Galaxies.

To know more…

- CESAR Booklets:
  - "The electromagnetic spectrum"
  - "Light and matter"

Outline

In this activity, students explore a number of astronomical objects of different types to see how their appearance change depending on the wavelength range of the observation. They learn about the electromagnetic spectrum and the different types of telescopes that exist. They also get an insight on how astronomers can study different phenomena happening in the Universe thanks to the different types of light produced in those processes.

Students should already know…

1. The concept and basic properties of waves.
2. The concept of light as an electromagnetic wave.
3. The concept of blackbody radiation.

Students will learn…

1. The different phenomena responsible for the emission of light by astronomical objects.
2. How astronomers use different types of light to study different objects or phenomena in the Universe.
3. The reasons for sending telescopes to space.
4. What information can be seen and extracted from an astronomical image.
5. Some basic ideas about a variety of astronomical objects.

Students will improve…

- Their understanding of scientific thinking.
- Their strategies of working scientifically.
- Their teamwork and communication skills.
- Their ability to apply theoretical knowledge to real-life situations.
- Their skills in the use of ICT.

Summary of activities

Title	Activity	Outcomes	Requirements	Time
1. Light in everyday life	Students discuss what different types of light exist and how we use them in normal life.	Students learn: • The properties of the electromagnetic spectrum. Students improve: • Their teamwork and communication skills. • Their ability to apply theoretical knowledge to real-life situations.	• Basic knowledge of the properties of waves. • Basic knowledge of the electromagnetic spectrum.	10 min
2. Getting familiar with ESASky	Students play with the tool to get familiar with it.	Students improve: • Their skills in the use of ICT.	None.	10 min
3. Observing across the spectrum	Students discuss the different types of telescopes that exist and what they are useful for.	Students learn: • The properties of the electromagnetic spectrum. • The different phenomena responsible for the emission of light by astronomical objects. • The types and purpose of ground-based and space telescopes. • About ESA missions. Students improve: • Their understanding of scientific thinking. • Their strategies of working scientifically. • Their teamwork and communication skills. • Their ability to apply theoretical knowledge to real-life situations. • Their skills in the use of ICT.	• Completion of Activity 1.	20 min

Title	Activity	Outcomes	Requirements	Time
4. The multi-coloured Universe	Students inspect images of a given astronomical object across the spectrum and speculate about the origin of the differences.	Students learn: • The properties of the electromagnetic spectrum. • The different phenomena responsible for the emission of light by astronomical objects. • How astronomers use different types of light to study different objects or phenomena in the Universe. • What information can be seen and extracted from an astronomical image. • Some basic ideas about a variety of astronomical objects Students improve: • Their understanding of scientific thinking. • Their strategies of working scientifically. • Their teamwork and communication skills. • Their ability to apply theoretical knowledge to real-life situations. • Their skills in the use of ICT.	• Completion of Activity 3.	30 min

Title	Activity	Outcomes	Requirements	Time
5. All the colours of…	Students do some in-depth research of an object of their choice and present it to the rest of the class.	Students learn: • The properties of the electromagnetic spectrum. • The different phenomena responsible for the emission of light by astronomical objects. • How astronomers use different types of light to study different objects or phenomena in the Universe. • What information can be seen and extracted from an astronomical image. • Some basic ideas about a variety of astronomical objects Students improve: • Their understanding of scientific thinking. • Their strategies of working scientifically. • Their teamwork and communication skills. • Their ability to apply theoretical knowledge to real-life situations. • Their skills in the use of ICT.	• Completion of Activity 4.	

Introduction

The constituents of the electromagnetic spectrum (Figure 1, also available in the Student Guide)) were gradually pieced together in the 19th and early 20th centuries, pioneered by William Herschel's discovery of infrared light. As technology developed, astronomers determined to study the sky across the spectrum, making amazing discoveries that showed that astronomical objects are often more complex than previously thought.

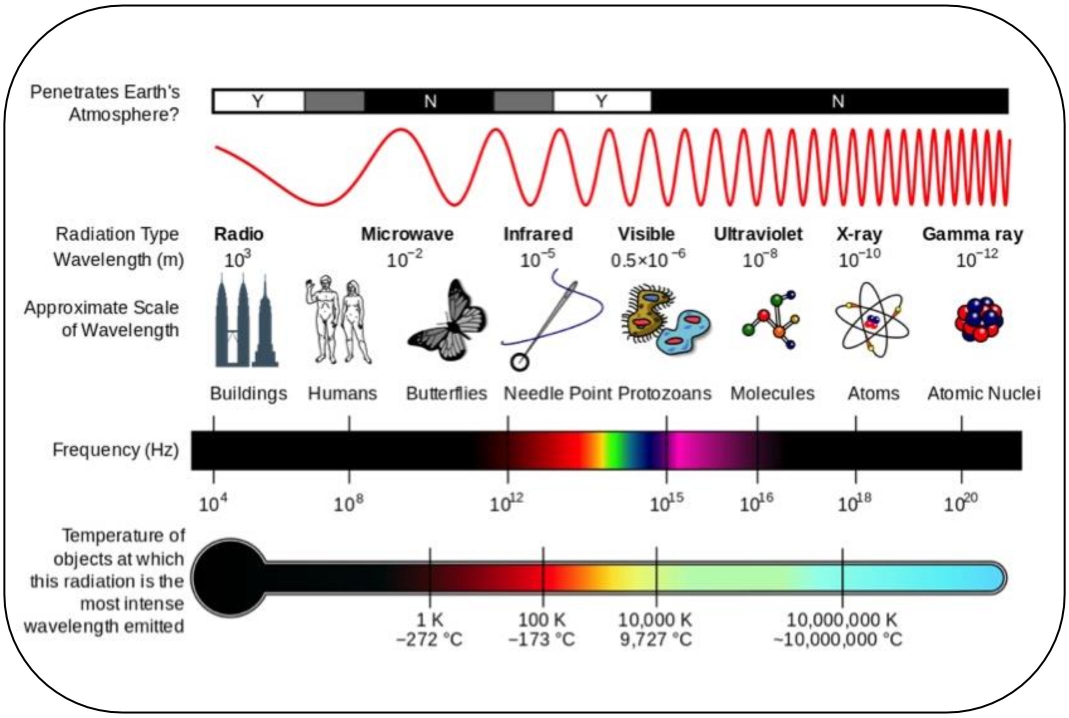


Figure 1: Properties of the electromagnetic spectrum. (Credit: Wikimedia Commons)

Table 1 (which also appears in the Student Guide) provides some examples of astronomical sources emitting over different portions of the spectrum, and the energy and temperature ranges they cover. Because several of these phenomena are associated, it is extremely important to observe astronomical objects in several wavelength ranges. This is the only way to fully understand what is going on in those objects.

However, multi-wavelength observations cannot be carried out from ground, as the Earth's atmosphere blocks most of the light frequencies –all except the visible, and some windows in the ultraviolet, infrared and radio. The bar at the top of Figure 1 provides information on whether the atmosphere is transparent (white), opaque (black) or partially opaque (grey) to light of a given wavelength.

In order to observe the full spectrum, telescopes must be placed in space, where the atmosphere is no longer a problem. This way, astronomical objects can be observed across the whole spectrum, and we can get the full picture of what is happening in them. Another reason to send telescopes to space, even if they detect a type of light observable from Earth, is to get rid of atmospheric distortions, thus improving the quality of the images. Figure 3 shows the ESA telescopes that operate or have operated in the whole electromagnetic spectrum.

*Table 1: Examples of astronomical sources emitting in each range of the electromagnetic spectrum.**

Type of radiation	Temperature	Energy	Typical sources
Gamma-rays	$>10^{8}$ K	$> 2\times10^{-14}$ J	Matter falling into black holes
X-rays	10^{6}-10^{8} K	2×10^{-17} - 2×10^{-14} J	Gas in clusters of galaxies Hot gas clouds in supernova remnants Stellar coronae Neutron stars
Ultraviolet	10^{4}-10^{6} K	5×10^{-19} - 2×10^{-17} J	Hot gas clouds in supernova remnants Very hot stars
Visible	10^{3}-10^{4} K	3×10^{-19} - 5×10^{-19} J	Stars Hot clouds of gas
Infrared	10-10^{3} K	2×10^{-22} - 3×10^{-19} J	Very cool stars Planets Cool clouds of dust
Microwave and radio	<10 K	$< 2\times10^{-22}$ J	Cool clouds of gas The Cosmic Microwave Background (CMB) Electrons moving in magnetic fields

***Adapted from:** *NASA/Imagine the Universe!*

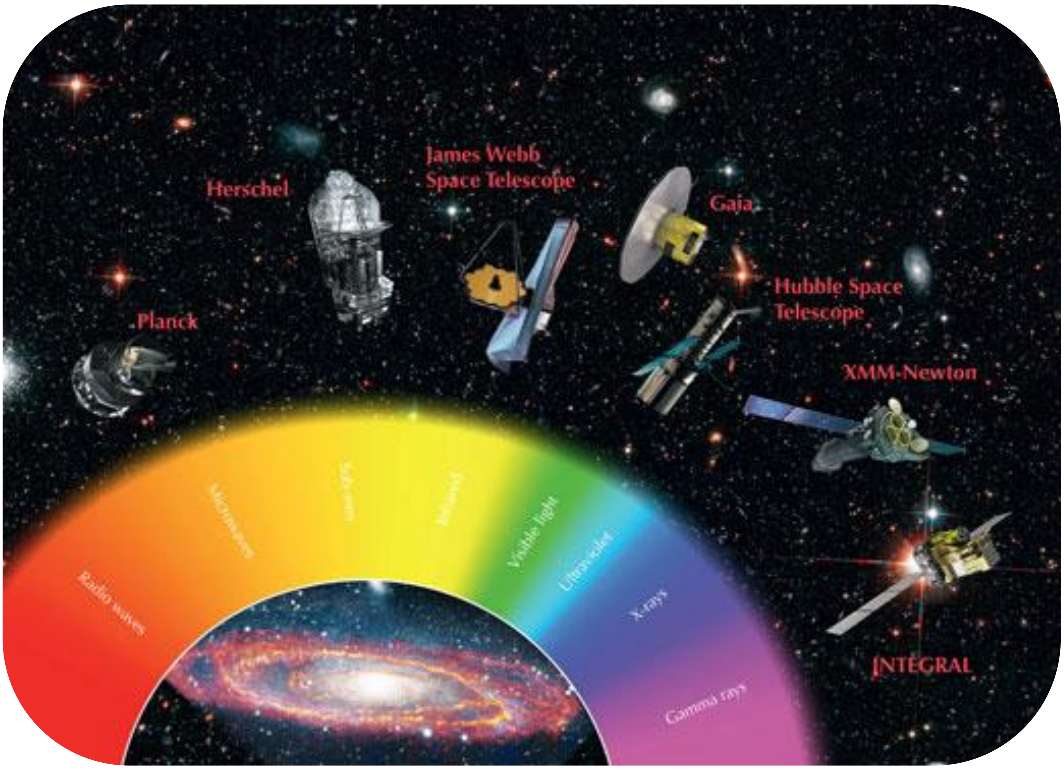


Figure 3: ESA's fleet of telescopes across the electromagnetic spectrum. (Credit: ESA)

Background

The light emission of stars and other astronomical objects is quite accurately described by a blackbody curve (Figure 3), meaning that this emission is mainly a consequence of the temperature of the object. This *thermal emission* follows the usual blackbody laws, and in particular Wien's law, which states that the blackbody curve of a star peaks at a wavelength that is related to the star's temperature following the relation:

$$\lambda_{max} = \frac{b}{T} \tag{3}$$

where *b* is Wien's displacement constant. Thus, many astronomical objects are most easily detected in the region of the electromagnetic spectrum where the maximum of a blackbody curve of the same temperature is located. In the case of stars, this range spans from part of the ultraviolet through the visible to the near-infrared.

The energy output of a blackbody also depends on the value of the maximum wavelength, following Stephan-Boltzmann's law:

$$E = \sigma T^4 = \sigma \left(\frac{b}{\lambda_{max}}\right)^4 \tag{4}$$

where σ is Boltzmann's constant. It follows that an object emitting most of its energy in the form of gamma rays will have a higher energy output than a body emitting mostly in radio waves.

There are, however, astronomical objects whose light emission does not follow a blackbody curve. In other words, the emission of light by these objects is not explained by their temperature alone. For example, electrons moving in a magnetic field and spiralling around the magnetic field lines will emit light in radio frequencies; this is called *synchrotron radiation*, and is an example of *non-thermal emission* usually found in the gas from supernova remnants (clouds created when the outer layers of a star are expelled in a supernova explosion).

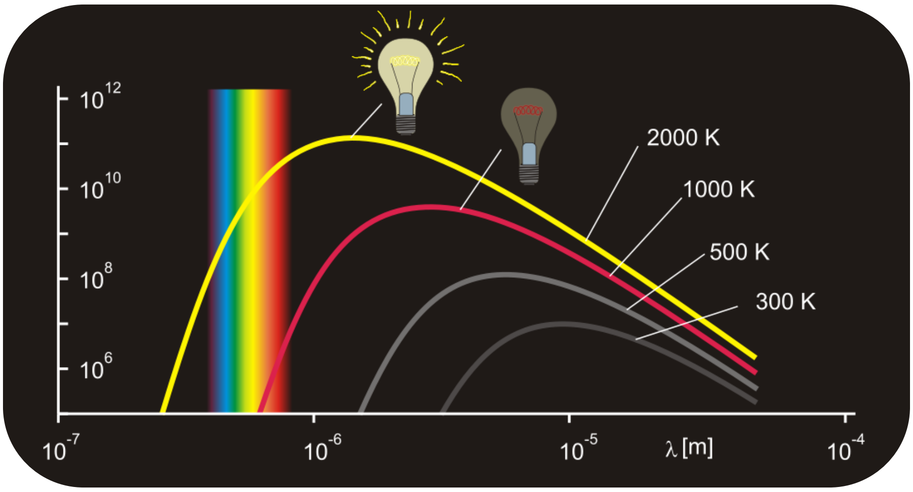


Figure 2: *Blackbody curves of different temperatures. (Credit: Wikimedia Commons)*

Activity description

Activity 1: Light in everyday life

In this activity, students reflect on their knowledge of the electromagnetic spectrum and how it is used in everyday life. The teacher can introduce the topic by assessing how familiar students are with the different types of electromagnetic radiation. Possible questions to guide the discussion are:

- *How would you explain what light is?*
- *What is the origin of the colours of the rainbow? What are the differences between the light you can see and the light you can't?*
- *What is radiation? Is all radiation harmful?*
- *How do we use invisible light in our everyday life?*

Answers to some of these questions will vary depending on the age and background of the students. For example, the eldest students may answer to the first question that light is both a wave and a particle, but the youngest students are not expected to know anything about Quantum Physics, so they are more likely to answer that light is a wave. All age groups should be able to understand that the different colours are the way our eyes interpret different wavelengths of light, and that the difference with other types of light is simply that they are wavelengths that human eyes cannot detect.

Although students have probably heard the term "radiation" before, they may not –especially the youngest ones– be able to provide an accurate definition for it, as energy transfer without contact between source and receptor. The teacher can provide examples (e.g. heating radiators) to help students understand that radiation does not always imply harm to living things.

The Student Guide asks a series of questions to complement this reflection. Students might need to do some research to answer the questions. This part of the activity could be completed as homework in preparation for the lesson.

Answers to the questions in the Student Guide

1. Can you think of everyday sources that emit visible and invisible light? What is this light telling us about those objects? Do you know some devices using different types of light? What is this light useful for in each case? Enter some examples in the table below:

Table A

Type of light	Sources and devices	Uses
Gamma-rays	Radioactive materials	Radiotherapy (medicine)
X-rays	Radiography machine Airport security scanner (for things)	Radiography (medicine) Seeing content of luggage bags
Ultraviolet	Sun Tanning bed	Getting tanned UV-therapy (medicine) Detecting forged bank notes
Optical (Visible)	Sun Light bulbs	Seeing things
Infrared	Living things Radiator Remote control device	Heating (Short-range) communications
Microwaves	Microwave oven Mobile phone Wi-Fi	Cooking Communications
Radio	Radio and TV station Radar	Communications Radar detection

2. Which types of light can be especially harmful to humans and other living beings on Earth? What can be the reason? (Hint: Use Table 1 and Figure 1)

   Students should be able to recognise that gamma and X-rays are the most dangerous radiation, as they can penetrate the human body and kill cells. Using Table 1 and Figure 1 (numbered in the same way in the Student Guide), they should conclude that the reason is that they are the most energetic and have the shortest wavelength (highest frequency). Following this reasoning, ultraviolet radiation will be the third most harmful radiation; they may be aware that UV light from the Sun is responsible for getting tanned and sunburnt.

   The teacher should clarify that electromagnetic radiation is harmful to humans when they are over-exposed to it. Because of the high energy and frequency of X-rays, exposure time to them (as in a radiography) must be really short to avoid damage. Intensity is also a factor: It is not the same to sunbathe on the beach on a cloudy day than on a sunny day, or to lie on a tanning bed; the amount of time required to get skin damage varies significantly, because of the different intensity of UV radiation.

   More advanced students might discuss the difference between ionising radiation (radiation energetic enough to strip electrons out of the atoms) and non-ionising radiation (radiation that is only able to move molecules, thus increasing the temperature of macroscopic bodies).

3. What type of light is emitted by a radiography machine, a mobile phone, and a TV remote control? If you had missed any of these devices, note them now in the table above.

   The purpose of this question is simply to prepare students for the following one, which compares these three devices that should be familiar to most of them. As noted in the table, the radiography machine uses X-rays, the TV remote control uses infrared light, and the mobile phone emits microwaves.

4. Have a look at Table 1 and note the relation between the type of light and the wavelength, frequency and energy carried by the electromagnetic wave. What device emits the least energetic radiation: a radiography machine, a mobile phone, or a TV remote control? Explain your answer.

   Using the information provided in their guides, students should note the following relationships: The shorter the wavelength the higher the frequency; the higher the frequency the higher the energy. More advanced students might state the following equations:

   $$f = \frac{c}{\lambda} \quad \text{and} \quad E = hf$$

   Where: *f* is the frequency, *λ* the wavelength, *c* the speed of light, *E* the energy, and *h* Planck's constant.

   Thus, by sorting the devices in order of the frequency they use, they will have them also ordered by energy. The conclusion is that the radiography machine emits the most energetic waves, and the mobile phone the least energetic (and potentially least harmful) radiation.

Activity 2: Getting familiar with ESASky (Optional)

This activity will enable students using *ESASky* for the first time to get familiar with the online application. If they have used *ESASky* before, this step may be skipped, and students can proceed to Activity 3.

To access *ESASky*, go to: http://sky.esa.int

For this activity, Explorer Mode is used. This mode is set by default on tablets and mobile phones, but not on laptops and desktop computers. If necessary, the mode can be selected in the welcome dialogue window, or with the switch on the top bar.

Students should work in pairs or small groups with one computer or tablet per group. Using the guidelines and object list provided in the Student Guide, they should practice the following:

- Panning and zooming around the sky.
- Moving from one object to another using the search box.
- Visualising the sky in different wavelengths.

Activity 3: Observing all types of light

In this activity, students use the Crab Nebula as reference object to find out about the telescopes that are used to observe the Universe at different wavelengths. They have to work out which telescopes are on the ground and which flown to space, and to compare the images of the nebula to see how they provide different pieces of information on the object.

The Crab Nebula, a supernova remnant with a central pulsar (fast-rotating neutron star emitting regular pulses of light), is a very prominent source all across the spectrum, and it has been observed by all missions that are selected by default in the ESASky skies menus.

Gamma-rays, hard X-rays and radio are not considered in this activity because the available maps have either too low resolution, too low coverage, or both. Although the submillimetre is regarded as a range in itself by professional astronomers, it is presented to students as "short microwaves" for the purpose of these activities. The mid-infrared range is not considered either.

Following the instructions in their guides, students first need to create a stack of maps in *ESASky* displaying the Crab Nebula at different wavelengths. They then have to identify if the telescopes that took the images of the Crab Nebula are likely to be ground-based or space-based, based on the information provided on the top of Figure 1 (*Penetrates Earth atmosphere?*).

Answers to the questions in the Student Guide

6. Complete the table below with information about the stack of maps you created for the Crab Nebula. You can find the name of the telescope that made the observations by clicking on the 'i' icon on the right of the drop-down menu (the name is under "Mission"). Use the information at the top of Figure 1 to decide if the telescopes in your stack are likely to be ground-based or spaced-based.

Table B

Type of light	Telescopes	Ground or space?
(soft) X-rays	XMM-Newton	Space
Ultraviolet	GALEX	Space
Optical (Visible)	DSS2	Ground
Near-Infrared (short infrared waves)	2MASS	Ground
Far-Infrared (long infrared waves)	Herschel	Space
Submillimetre (short microwaves)	Herschel	Space

5. Explain how you decided if a telescope is ground-based or space-based.

   The telescopes in the second column are identified in ESASky. If a particular type of light does not penetrate the Earth's atmosphere, it cannot be observed from ground. Knowing this, and with the information on the top bar of Figure 1, the third column of the table can be filled; grey areas on the bar indicate that only part of the light reaches the ground.

Students may be unsure about what to enter in the third column for the “Near-infrared” and “Far-infrared” fields; the teacher can explain that the shortest infrared wavelengths, being closer to visible light, are the ones penetrating the atmosphere. (Strictly speaking, there are some atmospheric windows at longer wavelengths in the mid-infrared and submillimetre domains, but it may not be necessary to tell students, as it may confuse them and is not necessary to complete the exercise.)

Some students may point out that atmospheric opacity is not the only reason to send telescopes to space. Although visible light gets through the atmosphere and reaches the Earth’s surface, a space-based optical telescope is not affected by atmospheric distortions, producing images that are sharper and more clear than those provided by a ground-based telescope of the same size. For example, the term “HST” in the map menu from the “optical” (visible) range corresponds to the Hubble Space Telescope, a space-based telescope that observes in visible light.

Students then take snapshots of the Crab Nebula in all ranges. They are asked to complete a table with the description of the object from what they can see in the image.

Finally, they use the information in Table 1 and the object description provided in question 7.c in their guide, together with the relation between type of light (frequency) and energy, to provide an explanation to the features seen in each image of the Crab Nebula. For example, they may describe the GALEX ultraviolet image as a “fuzzy red cloud”. They should then explain this observation as due to the presence of hot gas in the cloud. The teacher can later provide a more accurate explanation to the observed phenomena, based on the filled table in the Appendix (Table A1). Students write their hypotheses in the table and discuss them with other groups.

In this last part of the exercise, it is important that students make the connection between the bright source seen in X-rays and the central neutron star, making this image very different from the rest that show the cloud at different temperatures. In the submillimetre image, the teacher may choose to talk about accelerated charges in a magnetic field or not.

About the images

When comparing images in different wavelength ranges, it is important to point out to students that the colours are not real, and that the objects would not look like they do in the images if we were to see them with our own eyes –among other reasons, because our eyes are not capable of seeing light other than visible (optical). The images have been produced by combining black-and-white images taken in particular filters, and they have been artificially coloured to make the objects’ features easier to distinguish. Usually, blue indicates the shortest wavelength and red the longest.

Students may also note the differences in resolution (amount of detail) among images. As a general rule, resolution is best in the optical (visible-light) images and worst in both extremes of the spectrum. This is due to limitations in the telescopes and instrumentation.

Activity 4: The multi-coloured Universe

In this activity, students repeat the investigation completed in Activity 3 for one or more astronomical objects from a list. These objects have been selected to provide a representation of different types of astronomical phenomena. A description of each object, useful for the analysis, is displayed by ESASky in a pop-up window when the object is loaded; these descriptions are also provided in Table 2 (which is Table 3 in the Student Guide).

To start the study, students have to load the list of objects to explore, available in the application as a predefined target list with the name “CESAR Colours”. Students are first asked to inspect all targets and decide which ones change most across the spectrum, and which don’t (see below). They can move from one object to another by clicking on the name, or using the video-style buttons. Detailed instructions are given in the Student’s Guide. (Note that the first object in the list, M1, is the Crab Nebula discussed in the previous step.)

Answers to the questions in the Student Guide

4. Explore the objects in the list. Which object (or objects) looks similar in all images across the spectrum? Which object (or objects) shows the biggest differences? (Note that some objects may not have been observed by all telescopes.)

   Inspection of the objects in all the maps in the stack shows that M84, an elliptical galaxy, is probably the one showing less variation throughout the images. This object is closely followed by the Crab Nebula (M1), which looks quite similar in all images except in X-rays. On the other hand side, the objects showing the greatest variations all through the spectrum are the Bubble Nebula (NGC 7635), the Cigar Galaxy (M82) and the globular cluster NGC 4372. This latter object simply cannot be distinguished from noise in half of the images.

6. Pick an object in the list. Based on the description provided in the screen (and in Table 3), and with the help of the information in Table 1, complete the table in the next page for this object as you did for the Crab Nebula. (If the object has not been observed in a given wavelength range, leave that row of the table blank.)

   Completed tables with the images, image descriptions and interpretations for all objects can be found in the Appendix. In the “Type of light” column the mission (and instrument, if necessary) responsible for the observations is also indicated. It is important to bear in mind that, in some cases, there are more possibilities than the ones displayed in the tables given in the Appendix. For example, in the (soft) X-ray range, students can sometimes choose between more than one mission in the menu. On the other hand, in some cases (in particular, in the ultraviolet) they will have to inspect the available maps to find a mission that has observed their object, as not all missions have covered the whole sky. Note that, depending on the image picked by the students, some of the features discussed in the Appendix may not be so evident.

Activity 5: All the colours of…

As an extension activity, students can research their chosen object in more depth, and present their findings to the rest of the class.

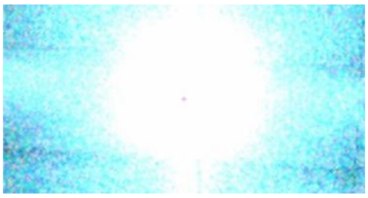
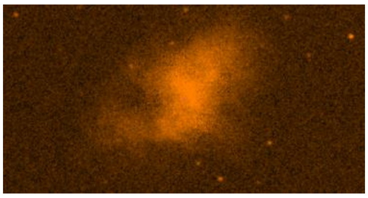
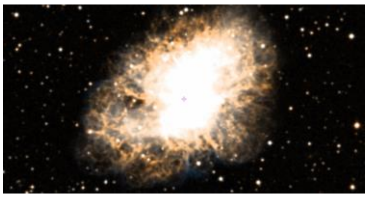
When discussing their findings in this or the previous activity, it is important that students understand that an object can emit light in a given wavelength range for different reasons. In particular, a cloud of gas can emit radio waves because of its low temperature (thermal emission) –this is the case, for example, of a nebula like NGC 7023 (the Iris Nebula)– or because of the effect of magnetic fields that accelerate charged particles in the gas (electrons) producing synchrotron radiation (non-thermal emission) –as in the case of M1 (the Crab Nebula).

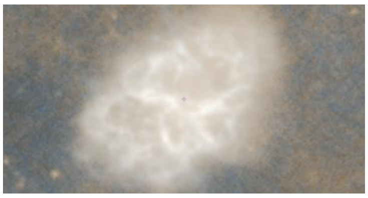
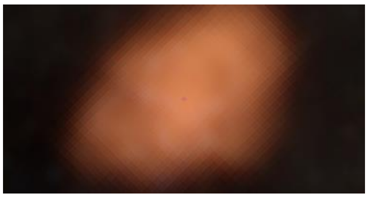
Table 2: *Astronomical objects to explore*

Object	Description
M1	The Crab Nebula, M1, is the remnant of a supernova observed by Chinese astronomers in 1054. A star much more massive than our Sun exploded at the end of its life, creating a cloud of dust and hot gas that is expanding into space. In the centre of the cloud, astronomers have discovered a neutron star that was once the core of the star. This is a very hot, small, and massive object, with a very strong magnetic field. It also spins very fast, emitting regular pulses of light like a lighthouse.
M82	Messier 82, also known as the Cigar Galaxy, is a so-called 'starburst galaxy'. These galaxies are forming stars at a much higher rate than normal galaxies; astronomers think this is a consequence of the interaction with another galaxy (in the case of M82, the neighbouring galaxy M81). The starburst region of M82, located in its centre, is 100 times brighter than the centre of our Milky Way galaxy, thanks to the high number of young, bright and hot massive stars it contains. Because these stars live fast and end their lives as supernovae, in M82, one such event happens every ten years.
M33	M33, the Triangulum Galaxy, is the third largest member of the Local Group of galaxies, after the Milky Way and the Andromeda galaxy: It has a diameter of about 60,000 light years, roughly 40% of the Milky Way. M33 is a spiral galaxy, meaning that the central spherical region of the galaxy is surrounded by a disk of cold gas and dust, which moves around the galactic centre forming the spiral arms. M33 contains two different populations of stars: The stars in the central region, or bulge, are relatively old, while the stars in the spiral arms are quite young, and new stars are continuously forming in this part of the galaxy.
NGC 4372	NGC 4372 is a globular cluster, that is, a spherical collection of stars very tightly bound by gravity. The density of stars increases as we move toward the centre of the cluster. NGC 4372 is part of the halo of our Galaxy, orbiting the galactic centre. Globular clusters like this one contain considerably more stars, and much older (thus brighter and cooler), than the less dense open clusters found in the Milky Way disk, and very little interstellar gas and dust.
NGC 7293	NGC 7293, known as the Helix Nebula, is a well-known planetary nebula, formed after an intermediate-mass star like our Sun got to the end of its life and shed its outer layers in the form of an expanding cloud of gas. The stellar core remains in the centre in the form of a hot white dwarf, which releases energy that heats up and ionises the surrounding gas.
IC 3583	IC 3583 is an irregular galaxy, that is, a galaxy with no distinct shape. It has a bar of stars running through its centre, suggesting it was once a spiral galaxy that got disrupted in a collision with its neighbour, galaxy Messier 90.
NGC 7635	NGC 7635, the Bubble Nebula, is a so-called emission nebula, a cloud of gas that is being heated up by a hot, massive star, causing it to glow and expand.
M84	Messier 84 is an elliptical galaxy belonging to the Virgo Cluster of Galaxies. This type of galaxy contains mostly aged stars, some of them ending their lives as supernovae, and little cold gas and dust.
NGC 7023	The Iris Nebula, NGC 7023, is a bright reflection nebula, that is, a cloud of interstellar dust that is reflecting the light of a nearby star. Contrary to an emission nebula, in this case the star is not hot enough to make the cloud glow in visible light.
NGC 3766	The Pearl Cluster, NGC 3766, is an open star cluster, that is, a group of stars that formed from the same interstellar cloud and have roughly the same age. This type of star cluster has no clear shape, and its members are only loosely bound by gravity, getting dispersed in the Galaxy as time goes by. NGC 3766 contains more than 130 known stars, most of them hot and blue, although two red supergiants (cool and red) are also part of the cluster.

Appendix: Objects information

Table A1

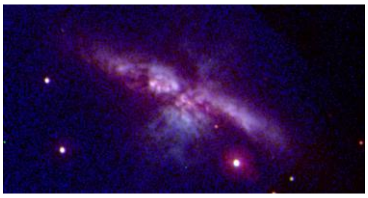
Object: Crab Nebula (M1)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		The image displays a bright source located at the centre of the nebula seen in the rest of images.	There must be a bright X-ray source at the centre of the nebula. Concretely, the emission comes from high-energy particles moving around the central neutron star, but this cannot be appreciated in the image due to its low resolution.
Ultraviolet (GALEX)		This image is similar in shape and configuration to those in the visible and infrared. We see the cloud shape, but not many details may be guessed due to the relatively low resolution.	The cloud gas is being heated by the central source and the energy from the explosion; that is why it glows, emitting ultraviolet light.
Optical (Visible) (DSS)		This image shows the cloud. Not much detail is appreciated in the central part, as the image is overexposed. Some filaments are observed at the edges.	As in the ultraviolet image, the gas is heated up, glowing in visible light. The filaments are result of the explosion that blasted the star's outer shells into space.

Near-Infrared (2MASS)		This image looks similar to the optical one. However, when comparing star patterns in both images, the pattern appears further away from the diffuse emission in the near-infrared image. We also see a higher number of stars.	Because near-infrared light has slightly longer wavelengths than visible light, they are not as much blocked by the dust in the cloud, allowing us to see stars that are too faint in the optical image. The hot gas is not so bright in this image, making the cloud emission less extended.
Far-Infrared (Herschel/PACS)		The cloud and the expanding filaments are also clearly seen in this wavelength range.	What we see here is the thermal emission from interstellar dust, that is, the light emitted by the dust due to its temperature. Hence, we can tell that the cloud not only contains gas, but also dust, and that this dust closely follows the patterns of hot gas seen in shorter-wavelength images.
Submillimetre (short microwaves) (Herschel/SPIRE)		Although the resolution is much worse, the cloud shape and some of its structure can be recognised in this image.	Supernova remnants like the Crab Nebula emit radio waves as a result of high-energy electrons fast moving in a magnetic field.

Remarks:

- In X-rays the XMM-Newton image is shown because this is the default map in this range. With the Chandra map (of better resolution), students can see the disk of hot gas around the neutrón star, as well as the gas jets that are being ejected by it.
- The last image (submillimetre range) may need some additional explanation. Students may explain it as thermal (blackbody) emission by cold gas. The teacher can point out that the gas is hot, or otherwise it would not be emitting in the visible and ultraviolet, and then introduce the concept of non-thermal emission.

Table A2

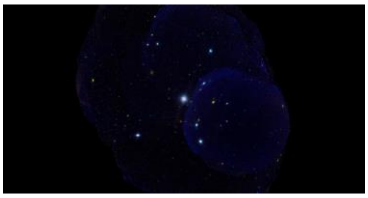
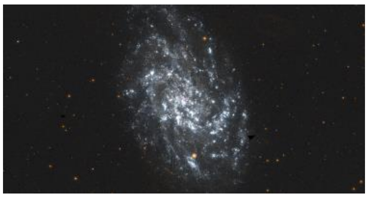
Object: Cigar Galaxy (M82)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		This image looks completely different from the rest of images of this galaxy. Most of the emission is concentrated in the central region. This area is surrounded by some X-ray emission that is perpendicular to the elongated shape seen in the other images.	The brightness of the centre suggests it is rich in supernova remnants and other strong X-ray sources (such as black holes). This is consistent with the object's description (see Table 2). The diffuse emission may be caused by extremely hot gas flowing away from the central part of the galaxy.
Ultraviolet (XMM-Newton/OM)		In this image, M82 has a very peculiar shape, with an elongated structure and wisps of emission nearly perpendicular to it. Some dark ridges are seen across the galaxy.	This peculiar shape is partially caused by obscuring dust that absorbs blue and near-ultraviolet light. The strong ultraviolet emission suggests the presence of many blue stars in this galaxy.
Optical (Visible) (DSS)		This image simply shows an elongated shape, overexposed in the central part, and surrounded by a fuzzy halo and some wisps of emission roughly perpendicular to this elongation.	The shape is suggestive of a disk seen edge-on, an indication that this could be a spiral galaxy seen from this particular perspective.

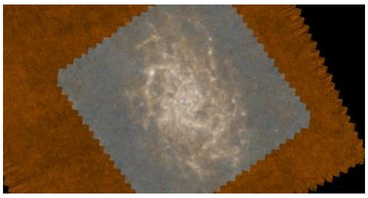
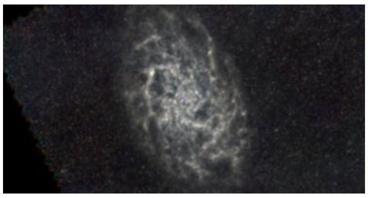
Near-Infrared (2MASS)		This image is very similar to the optical one, showing the elongated shape of the galaxy but without hints of other emission.	If this is indeed a spiral galaxy, the galactic disk must contain a lot of dust. In the near-infrared we are able to see through the dust. The saturation in the central part must come from the high density of stars in that region. This tells us that M82 contains lots of very red (cool) stars.
Far-Infrared (Herschel/PACS)		In this image, we see again an elongated shape surrounded by a halo, inside what looks like a gigantic cloud.	Far-infrared emission is mostly caused by cold dust. Hence, this observation proves that the galaxy indeed contains a lot of dust, especially in the disk (seen edge-on).
Submillimetre (short microwaves) (Herschel/SPIRE)		This image shows the central part of the galaxy as a nearly spherical shape, surrounded by a halo of emission.	In longer wavelengths, we are observing the gas present in the galaxy, which is cooler than the dust. Comparing this image with the one in the far-infrared, we see that the gas concentrates more in the centre than the dust.

Remarks:

- It is important that students understand that the telescopes cannot resolve the stars and other individual sources in this galaxy, and hence, what we observe in most images is the combined emission of billions of them.
- Although not strictly necessary for the exercise, the teacher may explain the connection between the colour of the stars and their evolutionary stage (young massive stars are hot and blue, while old massive stars are cold and red).
- Students are not expected to understand the nature of the diffuse emission in the XMM-Newton X-ray image. It is up to the teacher to provide this information.
- It may be interesting for students to compare M82 with M33, to see how an active galaxy like this one differs from a normal spiral galaxy like M33.

Table A3

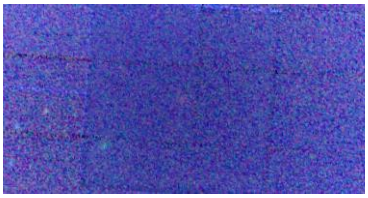
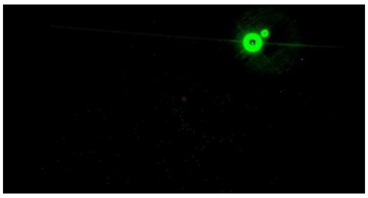
Object: Triangulum Galaxy (M33)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		This image shows a bright central sources surrounded by many others, not following any recognisable structure.	X-ray sources in galaxies are mainly remnants of the death of massive stars such as neutron stars and black holes. Hence, this observation tells us that M33 contains old stars, especially toward the central region.
Ultraviolet (GALEX)		In this image, the galaxy looks very similar to the optical image. We see what looks like a spiral galaxy, with a lot of arms moving around the centre.	Most of the ultraviolet emission is produced by very hot stars. Hence, this image is showing that the spiral arms of the galaxy contain lots of such stars.
Optical (Visible) (DSS)		The optical image shows a typical spiral galaxy, with a central yellow-white spherical part and the bluish spiral arms surrounding it. Some dark ridges are seen within the arms.	The bluish colour of the spiral arms suggests that they contain many hot (and massive) stars. The white-yellowish colour of the bulge (central part) suggests that stars in this part of the galaxy are not so hot in average. The dark areas indicate the presence of interstellar dust blocking visible light.

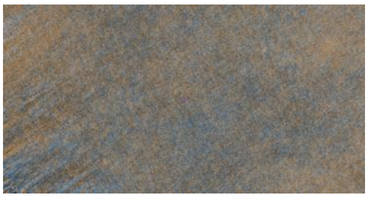
Near-Infrared (2MASS)		This image barely shows any spiral arms. They are only very weakly traced by some star patterns around the central, spherical part. The resolution of the image allows to confirm that the central part contains many stars.	Near-infrared light has longer wavelengths than visible light, and is not blocked by interstellar dust. We can thus see the stars hidden within the dust, or that are too cool and faint (thus very red) to be detected with visible light. The lack of a clear spiral pattern suggests that the spiral arms are rich in dust.
Far-Infrared (Herschel/PACS)		In this image, we recover the spiral pattern. The image resembles the optical and ultraviolet ones.	This image confirms that dust is a major component of the spiral arms. We can detect it at this wavelength because it is in the far-infrared that interstellar dust emits most of its energy, due to its cold temperature (about 100 K).
Submillimetre (short microwaves) (Herschel/SPIRE)		This image is very similar to the optical, ultraviolet and far-infrared ones, once more showing the spiral pattern.	In this case we are observing even cooler temperatures (as temperature decreases with wavelength), corresponding to the emission of cold gas in the galaxy. Hence, the image is telling us that the spiral arms of the galaxy contain a lot of cold gas.

Remarks:

- As in the case of M82, students have to keep in mind that in those ranges where stars are particularly prominent (ultraviolet, visible and near-infrared), the emission is dominated by the light from bright, massive stars, even though those stars cannot be resolved individually.
- Although it is not strictly necessary to talk about the evolutionary stage of the different stellar populations, students may be encouraged to make the connection between the optical colours of the stars and their age based on their location within the galaxy and the description given by the application (and Table 2).

Table A4

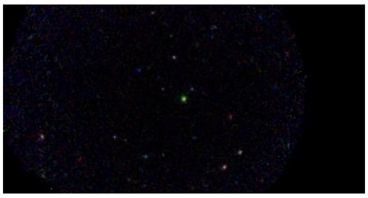
Object: NGC 4372			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		Only a few weak X-ray sources are visible in the area where the cluster is located. Essentially, what we see is noise.	Very few supernova explosions and their products (neutron stars, black holes) are present in the cluster.
Ultraviolet (XMM-Newton/OM)		The cluster is not detected in the ultraviolet. We only see the unrelated bright blue star seen in the visible image, and a neighbouring star.	The lack of ultraviolet emission indicates that the cluster does not contain hot stars. This is in agreement with the observations at longer wavelengths (visible and near-infrared).
Optical (Visible) (DSS)		The image shows a roughly spherical grouping of yellowish stars, with increasing stellar density toward the centre. A bright blue star (unrelated) is seen to the North-West of the cluster.	The lack of blue stars (young, massive stars) in the cluster suggests that the stars are relatively old. The spherical shape is a consequence of the mutual gravitational attraction of the stars in the cluster.
Near-Infrared (2MASS)		The image in this range is very similar to the optical one: a spherical grouping of stars with increasing density toward the centre. The blue star in the optical image is not so prominent here.	This image confirms that the stars in the cluster are red and cold, as they have remarkable emission in the near-infrared. The fact that the bright blue star in the optical image does not stand out confirms it is much hotter than the cluster stars.

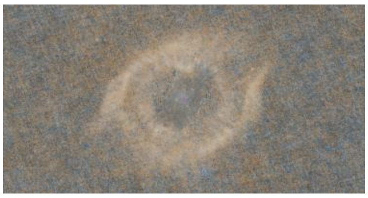
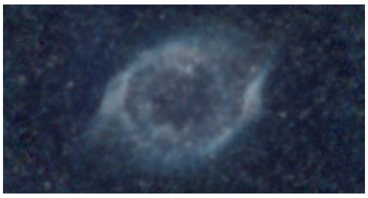
Far-Infrared (Herschel/PACS)		We only see noise in this image: The cluster is not detected.	This observation (or lack of it) indicates that the cluster does not emit much in this wavelength range. Since the most prominent source in the far-infrared is interstellar dust, this means that the cluster contains very little dust.
Submillimetre (short microwaves) (Herschel/SPIRE)		We see no hints of the cluster in this image.	Since the cluster does not emit light in this range, which is dominated by the emission from the cold interstellar gas, it follows that the cluster contains very little gas.

Remarks:

- The relatively high distance of globular clusters (which are part of the Galactic Halo) must be taken into account to understand that only bright, massive stars are observed.
- If wished, the teacher may explain to the students that the lack of gas and dust implies that very few new stars can form in this cluster. They can then compare this cluster with the open cluster NGC 3766.

Table A5

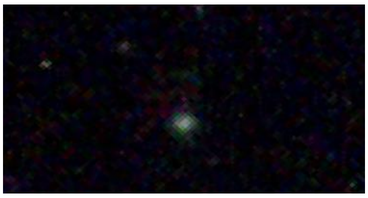
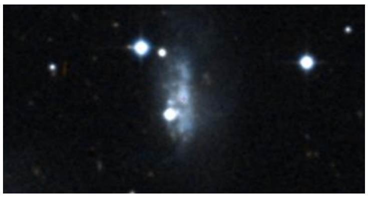
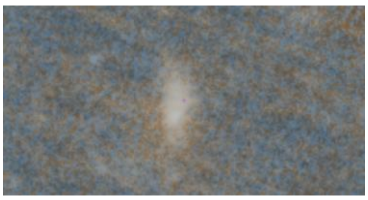
Object: Helix Nebula (NGC 7293)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		We don't see the nebula in this image, only the X-ray emission from the central source and some other weaker sources.	The central source must be the white dwarf at the centre of the nebula, the remains of a star like our Sun that got to the end of its life. White dwarfs are not such strong X-ray emitters as neutron stars or black holes. The other sources seen in the image are unrelated to the nebula.
Ultraviolet (GALEX)		The image is very similar to the optical one, but here the ring looks darker and the central circular area smaller. We can also see a strong ultraviolet source in the centre of the nebula, which is not so prominent at shorter wavelengths.	The emission in the central area confirms that the gas in the nebula is being heated up by the central source. The dark cloud edges indicate the presence of dust that is blocking ultraviolet and blue light. The strong emission of the central source indicates its very high temperature.
Optical (Visible) (DSS)		This image shows a glowing cloud. The central, roughly circular blue region is surrounded by a sort of lighter blue ring. The edges are darker and diffuse. Some white sources (probably stars) are seen within the cloud.	The gas in the nebula is heated up and ionised by the central white dwarf. The presence of dust is indicated by the obscuration in the edges of the nebula.
Near-Infrared (2MASS)		The nebula is not seen in this image. Only an apparently irrelevant star field is visible.	Near-infrared light, having longer wavelengths than visible light, is able to get through the cloud dust and unveil what is behind it.

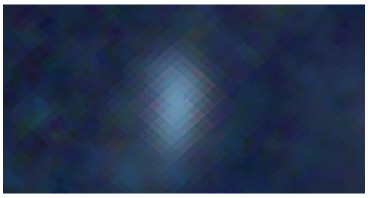
Far-Infrared (Herschel/PACS)		The cloud shape observed in visible and ultraviolet light is reproduced in this image, but in negative: What is dark in the other images is emitting light here, and viceversa.	We are observing the emission from the dust in the cloud. The areas where more dust is present, which were seen dark in the visible and ultraviolet, are now the brightest.
Submillimetre (short microwaves) (Herschel/SPIRE)		This image is very similar to the far-infrared one, showing the nebula as a negative of the visible and ultraviolet images.	Here we are observing the emission from the gas in the nebula.

Remarks:

- In the optical image, the cloud could be blue for two reasons: either the dust in it is reflecting light from the central source, or the gas is heated up and ionised by this source. In case both possibilities are mentioned by the students, the teacher may point out that a way to test them is to observe the nebula at other wavelengths; cold gas and dust will not glow in the ultraviolet.
- Students may compare the Helix Nebula with the Crab Nebula: What are the similarities? What are the differences?

Table A6

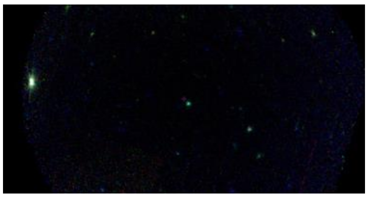
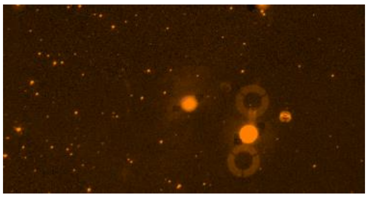
Object: IC 3583			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		We only see an X-ray source, whose location corresponds to the lower part of the blue elongated nebulosity seen in the visible image.	This could be the centre of the former barred spiral galaxy, as most galaxies display X-ray emission in their central regions due to the presence of black holes.
Ultraviolet (GALEX)		The bright stars seen in the visible image look much redder than the stars in the diffuse elongated shape (visible despite the low resolution).	The stars within the galaxy must be very hot. The other stars, being redder, are probably foreground and unrelated to the galaxy.
Optical (Visible) (DSS)		A diffuse, bluish elongated shape is seen in this image, with a bright source in the South-East part of it and some other bright stars (probably unrelated) nearby. Some dark ridges are seen within the nebulosity.	This elongation may be the remains of a bar in a once barred spiral galaxy. The bluish colour suggests the presence of hot stars. The dark areas are probably caused by the absorption of visible light by interstellar dust in the galaxy.
Near-Infrared (2MASS)		In this image, we can only distinguish the bright stars seen in the visible image, and the bright source observed within the diffuse elongated shape in that same image.	With near-infrared light we are able to see through the nebulosity. However, the telescope is not powerful enough to observe the galaxy.
Far-Infrared (Herschel/PACS)		In this image, again an elongated shape is seen.	In this wavelength range, we are observing thermal emission from interstellar dust within the galaxy.

Submillimetre (short microwaves) (Herschel/SPIRE)		This image looks very similar to the far-infrared one, again displaying an elongated, diffuse shape.	We are observing the emission from the interstellar gas in the galaxy.

Remarks:

- Students may compare this galaxy with M33 and M84, to see the similarities and differences with other types of galaxies (spiral and elliptical).

Table A7

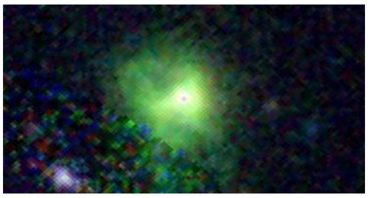
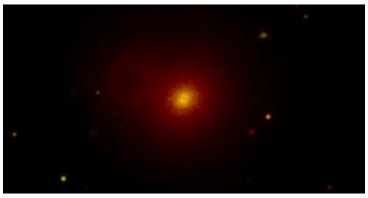
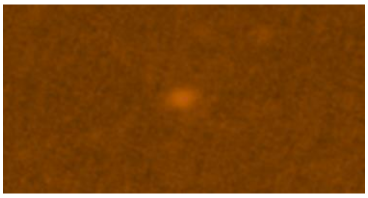
Object: Bubble Nebula (NGC 7635)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		The image shows a few prominent X-ray sources. The one in the centre corresponds to the hot star seen half-hidden in the cloud in the optical image. The one to the south-west of it is the blue star seen next to the cloud in the optical image.	The X-ray emission suggests that both stars are very hot and have strong coronal activity.
Ultraviolet (GALEX)		In this image we see the emission from a number of stars, many of them with counterparts in the optical image below. The brightest source is the blue star seen to the West of the nebula in the optical image, the second brightest is the star half-hidden in the cloud in that image.	This image confirms that the star within the cloud is hot enough to ionise the nebula. Probably the bubble seen at longer wavelengths is the result of photoevaporation and expansion of the cloud by the winds of this star. The image also shows other hot stars in the area, which may or may not be related with the cloud.
Optical (Visible) (DSS2)		The image shows a diffuse cloud with a reddish glow and some dark areas. A bright star is seen half-hidden in the cloud, in one of the edges of a sort of “bubble”. Other fainter stars are seen within the nebulosity or next to it, including a bluish star to the west of the cloud.	The gas in the nebula is ionised by the hot star within it, what causes the reddish glow. The dark areas in the cloud are due to light absorption by the cloud dust.

Near-Infrared (2MASS)		We see barely any nebulosity, except near the bright star from the optical image (not so bright in this image here). Only near this star, a patch of diffuse emission is observed. Some stars hidden by the cloud in the optical image are revealed.	Having longer wavelengths, near-infrared light gets through the dust, showing the stars hidden within or behind the cloud.
Far-Infrared (Herschel/PACS – Gal.)		In this image, we see the cloud again, with a bluest area corresponding to the position of the diffuse light patch in the near-infrared image. Part of the bubble also shines with bluish light. The cloud gets less blue as we move away from this region.	As in the visible light image, blue colour is assigned in this image to the shortest wavelength. Hence, that region in the nebula is hotter than the surroundings, probably due to the vicinity of the hot star.
Submillimetre (short microwaves) (Herschel/SPIRE)		Despite the low resolution, this image closely resembles the far-infrared one. Again a bluer area can be seen in the location of the near-infrared patch.	We now see the emission from the gas in the nebula.

Remarks:

- Students may be puzzled by the rings visible in the ultraviolet image. The teacher should explain that they are artefacts of the image, and not real features in the sky.

Table A8

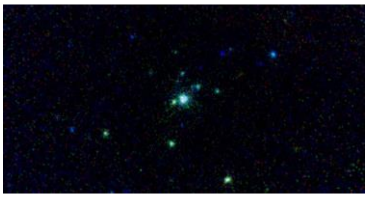
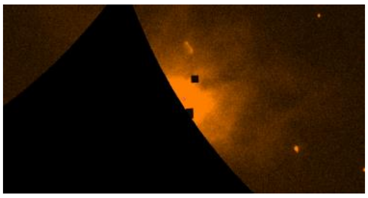
Object: Messier 84 (M84)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		The image shows extended and more irregular emission than in the rest of wavelengths.	The X-ray emission is mainly caused by supernovae and the remains of massive stars (neutron stars and black holes).
Ultraviolet (XMM-Newton/OM)		The image shows a faint elongated source.	The image suggests that the galaxy contains some relatively hot stars, but the faintness of the ultraviolet emission, compared to the optical and near-infrared, suggests that the content in hot stars is not so high as in cold stars.
Optical (Visible) (DSS)		In this image, the galaxy shows spherical shape and white-yellow colour.	The colour of the galaxy is caused by the light emission of the stars in it. Based on the optical colour, these stars must be relatively cold.
Near-Infrared (2MASS)		The appearance of M84 in this image is very similar to the visible light image.	This observation suggests that M84 has a high content of cool (very red) stars.
Far-Infrared (Herschel/PACS)		In this image, the galaxy appears as a relatively faint spherical structure, smaller in size (thus less bright) than in shorter wavelengths.	Because the emission in this range is mainly caused by interstellar dust, this image is telling us that M84 contains some dust.

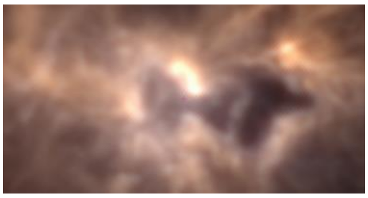
Submillimetre (short microwaves) (Herschel/SPIRE)		This image is very similar to the far-infrared image, showing the galaxy as a faint spherical source.	The emission in this range is caused by cold dust, confirming that M84 also contains interstellar dust.

Remarks:

- Students may compare this galaxy with M33, to see the differences in the stellar population between elliptical and spiral galaxies.

Table A9

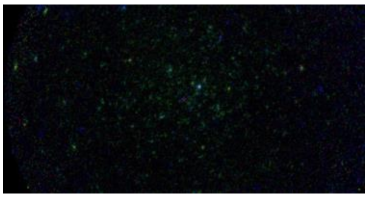
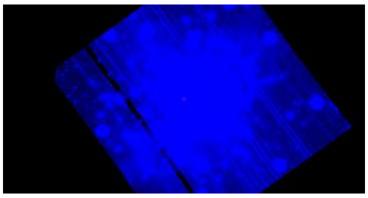
Object: Iris Nebula (NGC 7023)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		This image reveals the presence of several X-ray sources in the central region of the nebula.	Hot stars or stars with high coronal activity must be present inside the nebula. The brightest of them seems to correspond to the star whose light is being reflected by dust in the visible.
Ultraviolet (GALEX)		Only part of the cloud has been observed in the ultraviolet. We see some diffuse emission in the central region of it.	The ultraviolet emission must come from the same source that is producing the blue light scattered by the cloud in the visible image: a relatively hot star.
Optical (Visible) (DSS)		This image shows a dark cloud. The central part looks white because it is overexposed, and it is surrounded by blue nebulosity.	The dust in the cloud is blocking most visible light, preventing us to see what is inside and behind the cloud. In the central part, light from a hot source within the cloud is being scattered. The nebula looks blue because blue light gets more scattered than red light.
Near-Infrared (2MASS)		In the near-infrared, we see no cloud, only a patch of diffuse emission surrounding the central star, that is now unveiled, as well as many other stars in the area.	Using near-infrared light we can see through the dust to confirm that the source of the light scattered by the cloud in the visible is a star in the centre of the nebula. We can also see many other stars that are hidden behind the dust in the optical image.

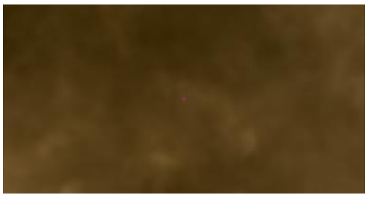
Far-Infrared (Herschel/PACS – Gal)		In this image the cloud is seen again, this time in positive –emitting light. The central region shows a sort of cavity in the location where the central star is observed in the near-infrared.	We are now seeing the emission of the dust itself, because of its low temperature. The radiation from the central star seems to be carving a hole in the cloud.
Submillimetre (short microwaves) (Herschel/SPIRE)		This image looks very similar to the far-infrared one: We see the cloud and the central cavity where the star is located.	This time we are seeing the thermal emission from the gas in the cloud, which is cooler and dominates in this wavelength range.

Remarks:

- Depending on the zoom they use, students may not find the ultraviolet image. This is ok; they are warned in the Student's Guide that some objects may not have images available in all wavelength ranges.
- It may be interesting for students to compare this reflection nebula with the Bubble Nebula (an emission nebula).

Table A10

Object: Pearl Cluster (NGC 3766)			
Type of light	**Image**	**Description**	**Explanation**
(soft) X-rays (XMM-Newton)		In this image, we can identify many stars in the cluster as weak X-ray sources.	The detection of these stars in X-rays confirms that these stars are very hot and/or have strong coronal activity.
Ultraviolet (XMM-Newton/OM)		We can recognise the cluster from the visible image in this ultraviolet image. However, the image is less clear due to the impossibility of separating the stars in the central part of the cluster, both because of the low resolution and of the brightness of the stars, that saturate this central part.	This image confirms that most stars in the cluster are very hot, and thus prominent ultraviolet sources.
Optical (Visible) (DSS)		This image shows a rich cluster of bluish stars of different brightness. A couple of more reddish stars are also visible; they look similarly bright to some of the blue stars in the cluster.	This observation indicates that most stars in the cluster are hot and blue, but two of them are red and cold.
Near-Infrared (2MASS)		In this image, two stars are clearly brighter than the rest. Their location coincides with that of the red stars in the visible image.	The fact that these two stars stand out so clearly in the near-infrared confirms that they must be cold and red: they are brighter in near-infrared wavelengths than in the visible, contrary to the hot and blue stars.

Far-Infrared (Herschel/PACS)		We don't see the cluster in this image, just some emission of infrared light all over the region.	This image is simply telling us that there is some dust between the stars and us, but the cluster is not associated with any nebula.
Submillimetre (short microwaves) (Herschel/SPIRE)		As in the far-infrared image, the cluster is not seen in this image, just some cloudy emission.	Similarly to the image above, all what we can tell from this image is that some interstellar gas is present.

Remarks:

- Students may compare the Pearl Cluster with NGC 4372 and discuss the differences in the stellar content of both types of clusters.
- They may also compare both clusters with the Iris and Bubble nebulae and discuss the differences in the stars they contain and their content in gas and dust. If wished, this comparison could serve as a transition to the topic of stellar evolution.

Links

Other related Science Cases

- *Exploring the Interstellar Medium:* http://cesar.esa.int/index.php?Section=Exploring_the_Interstellar_Medium
- *The Secrets of Galaxies:* http://cesar.esa.int/index.php?Section=The_Secrets_of_Galaxies

Astronomical objects

For students:

- CESAR Booklet: *The Interstellar Medium* http://cesar.esa.int/upload/201801/ism_booklet.pdf
- CESAR Booklet: *Stellar evolution* http://cesar.esa.int/upload/201801/stellarevolution_booklet_v2.pdf
- CESAR Booklet: *Galaxies* http://cesar.esa.int/upload/201801/galaxies_booklet.pdf

For teachers:

- Stellar processes and evolution: http://sci.esa.int/education/36828-stellar-processes-and-evolution/
- Galaxies and the expanding universe: http://sci.esa.int/education/36827-galaxies-and-the-expanding-universe/

The electromagnetic spectrum and ESA missions

- ESA's fleet across the spectrum (poster): http://sci.esa.int/education/59465-esa-fleet-across-the-spectrum-poster/

For students:

- CESAR Booklet: *The electromagnetic spectrum* http://cesar.esa.int/upload/201711/electromagnetic_spectrum_booklet_wboxes.pdf
- TED-ED: *Light waves, visible and invisible* https://ed.ted.com/lessons/light-waves-visible-and-invisible-lucianne-walkowicz

For teachers:

- *A brief history of infrared astronomy:* http://sci.esa.int/herschel/59550-a-brief-history-of-infrared-astronomy/
- Science@ESA: *The full spectrum* (video) http://sci.esa.int/education/44685-science-esa-episode-1-the-full-spectrum/
- Science@ESA: *The untamed, violent universe* (video) http://sci.esa.int/education/45421-science-esa-episode-5-the-untamed-violent-universe/
- Science@ESA: *Exploring the infrared universe* (video) http://sci.esa.int/education/44698-science-esa-episode-3-exploring-the-infrared-universe/
- Blackbody radiation: http://sci.esa.int/education/48986-blackbody-radiation/

- Science in School: *More than meets the eye: the electromagnetic spectrum* http://www.scienceinschool.org/2011/issue20/em
- Science in School: *More than meets the eye: the exotic, high-energy Universe* http://www.scienceinschool.org/2012/issue24/em
- Science in School: *More than meets the eye: unravelling the cosmos at the highest energies* http://www.scienceinschool.org/2011/issue21/em
- Science in School: *More than meets the eye: the cold and the distant Universe* http://www.scienceinschool.org/content/more-meets-eye-cold-and-distant-universe

ESASky

- General documentation: https://www.cosmos.esa.int/web/esdc/esasky-how-to
- *How to use ESASky in Explorer Mode* (video): https://youtu.be/m14JlkqdiUE
- *How to explore multi-wavelength skies* (video): https://www.youtube.com/watch?v=zkJkhSDr0nQ