CESAR Science Case

Exploring the Interstellar Medium

Studying the gas and dust between the stars

Student Guide

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Background

Outer space is often imagined to be completely empty, but there is in fact matter between the stars. Astronomers call this matter *the interstellar medium* or ISM for short. About 99% of this medium is gas, and 1% is dust that is mostly made of iron, silicates, carbon and dirty ice. The gas component is about 90% hydrogen and 10% helium, with traces of other elements.

The ISM is very cold and much less dense than any vacuum created in a laboratory. The temperature of the dust is typically 100 K, while the gas can be as cold as 10 K. Because of the low temperature of the ISM in order to observe it directly it is necessary to use telescopes that are able to detect light at wavelengths that are longer than visible light (infrared and radio; see Figure 1).

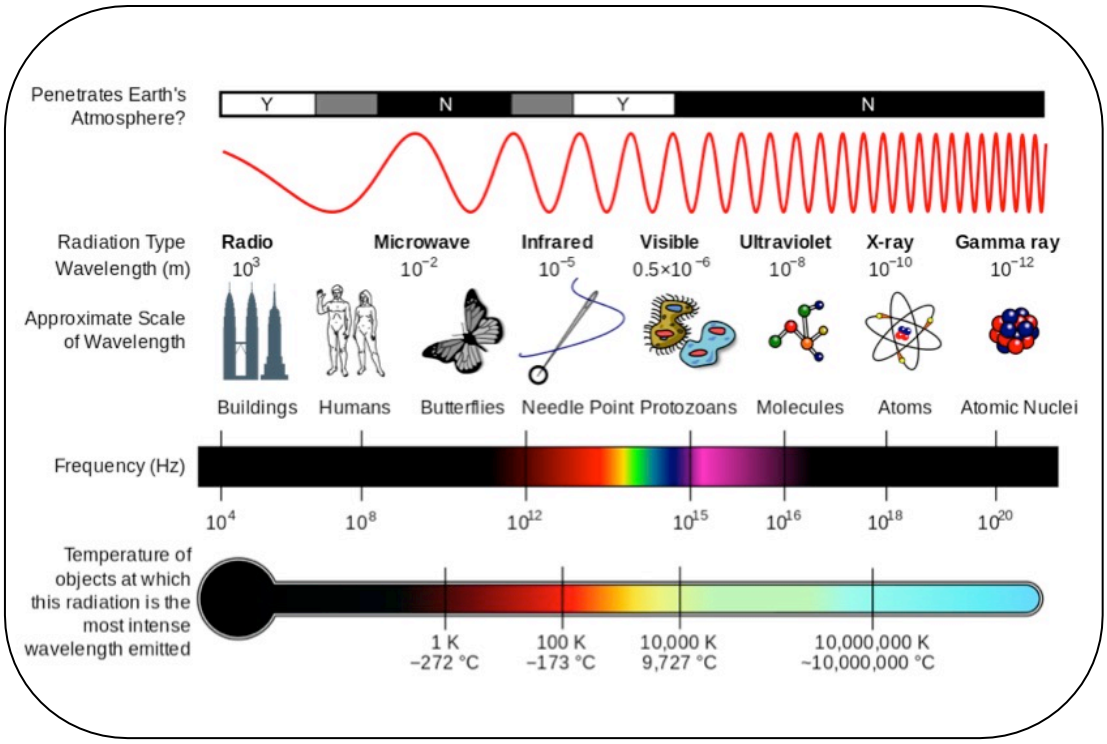


Figure 1: *Properties of the electromagnetic spectrum. (Credit: Wikimedia Commons)*

Even though the ISM is not observed directly in optical (visible light) images it is possible to see other effects (Figure 2):

- Dust grains can block light at optical wavelengths. This creates apparently empty areas of space (with no stars) in optical images.
- Sometimes light is not completely blocked. Dust absorbs and scatters blue light more than red light; thus, mostly red light passes through it. Consequently, a star positioned behind the dust will look redder than it really is. This effect is called *interstellar reddening*.
- Since part of the light is lost, a star will also look fainter than expected. This phenomenon is known as *optical extinction*.

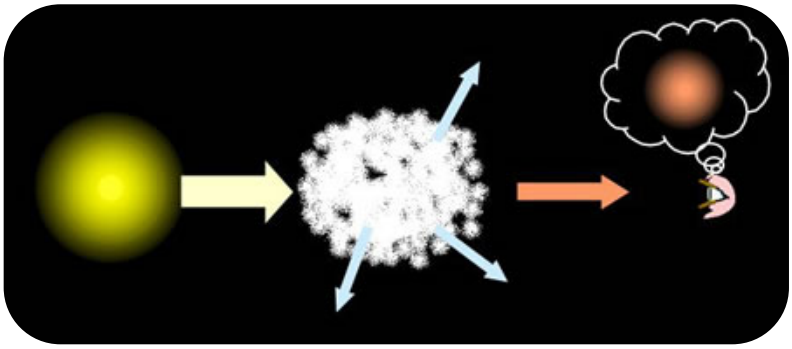
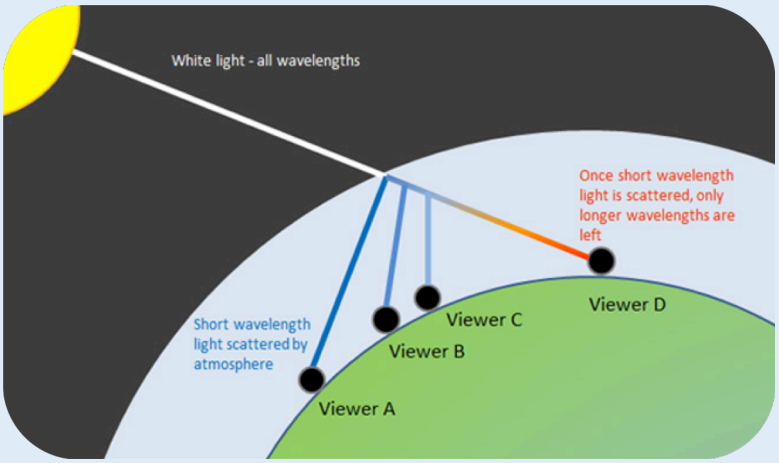


Figure 2: *Effects of the ISM: A star behind it will look redder and fainter than it really is. (Credit: COSMOS, the SAO Encyclopedia of Astronomy)*

Did you know?

Have you ever wondered why the sky is blue, or why sunsets are red? The reason is that the Earth has an atmosphere. As light from the Sun goes through the atmosphere, gases and particles absorb some of it, and some of it is scattered in all directions. Blue light is more scattered than red light, and so the result is a blue sky.

When the Sun is low in the sky, light from it has to travel further through the atmosphere to reach our eyes. Thus, the amount of scattering increases, and if we look in the direction of the Sun, we mostly see red light, hence a red sunset. In addition, because so much light is lost, the Sun does not look so bright at sunset as it does at other times of the day.



Scattering of blue light by the atmosphere creates a blue sky and red sunsets. (Credit: askascientist.co.uk)

This effect of the atmosphere on sunlight is similar to that of the interstellar dust on the light from stars located within or behind it.

Learning about the Interstellar Medium

Activity 1: Infrared light

In this activity, you will become familiar with one of the most important tools astronomers use to study the interstellar medium: infrared light. This type of light was discovered in 1800, when astronomer William Herschel (1738-1822) carried out an experiment to split up white light into the colours of the rainbow using a glass prism. He measured the temperature of the different colours with a thermometer. Herschel found that the temperature increased from blue to red. Out of curiosity, he also placed the thermometer next to the red, where no colour was visible, and found the temperature increased further. Herschel had discovered a colour of light invisible to human eyes, with longer wavelengths and lower frequencies than visible light (see Figure 1).

Even though we cannot see infrared light, it can be detected with appropriate devices. Figure 3 shows some examples of common things observed by an infrared camera. (Note that the colours in the infrared images are not real, they simply indicate the relative brightness of the light, increasing from black to white through magenta, blue, green, red, and yellow. This brightness in turn is an indication of the body's temperature.

Look at the images in Figure 3 and answer the questions below. If you have access to an infrared camera, you could take your own images and use them instead.

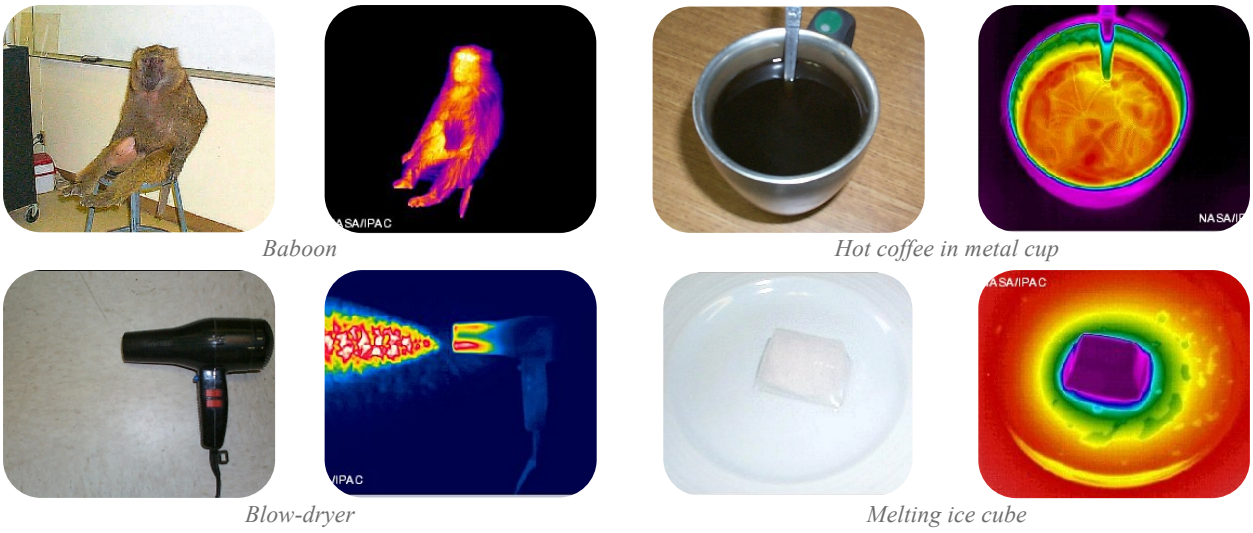


Figure 3: *Everyday things observed in visible (left) and infrared light (right). (Credit: coolcosmos.ipac.caltech.edu)*

1. Look at the pairs of images in Figure 3. Each pair shows the same image, one taken in visible light and the other in infrared light.

   a. In what sense are the two images in each pair similar? In what sense are they different?

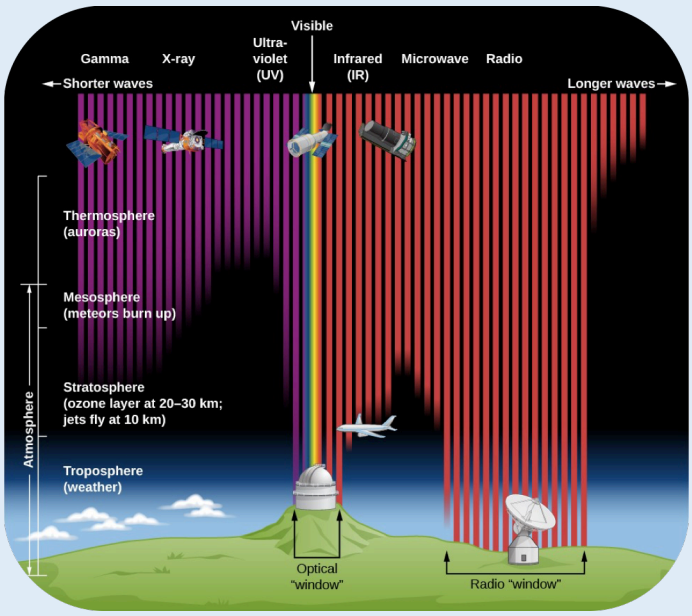
   b. In the visible light images, do we see the light emitted by the objects? If not, why can we see them? Is it the same for the infrared images?

Most bodies emit light because of their temperature. The wavelength (and frequency) at which this emission is highest depends on the temperature of the object. Stars and other objects emitting most of their light in the visible portion of the electromagnetic spectrum have temperatures between about 3000 and 10 000 K.

2. If the objects in Figure 3 emit mostly infrared light, do they have higher or lower temperatures than objects that emit visible light? Use Figure 1 to justify your answer.

Did you know?

It is not by chance that our eyes are adapted to see the light a particular region of the electromagnetic spectrum. The Earth's atmosphere blocks most of the light coming from outer space, except for a few "windows" in the visible range, the near-infrared, and radio. To observe other wavelengths, including the far-infrared range, telescopes must be placed above the atmosphere, in space.



Most invisible light is blocked by the atmosphere (Credit: STScI and Chandra)

In 2009, ESA launched the Herschel Space Observatory, which was operational until 2013, observing in the far-infrared and submillimetre (short microwaves). In these activities, you will work with images taken with this telescope, the largest infrared telescope in space to date.

Astronomers divide the infrared into three wavelength parts (or spectral regions): near, mid and far-infrared. Each part covers a range of wavelengths that correspond to distinct range of temperatures, as summarised in Table 1.

Table 1: *Types of infrared light.*

Spectral region	Wavelength	Temperature
Near-infrared	1×10^{-6} - 5×10^{-6} m	700 - 3,000 K
Mid-infrared	5×10^{-6} -2.5×10^{-5} m	100 - 700 K
Far-infrared	2.5×10^{-5} - 2×10^{-4} m	15 - 100 K

3. In humans, normal body temperature is around 36 ºC. Based the information in Table 1, in which region of the infrared do humans emit most light? Explain your answer. (Remember that 0 K = -273 ºC).

Activity 2: Getting familiar with ESASky (optional)

In this and the following activities, you will use the *ESASky* web application to explore real images of space and the ISM. If you have not worked with it before, take a few minutes to become familiar with the tool.

1. Load *ESASky* in your browser by entering:

   http://sky.esa.int

2. When loading the application, it will display an astronomical object and a pop-up window with a brief description of it. Note that this image is actually a map of the entire sky. You can zoom in and out the object, and pan to move to other regions of the sky.

3. To view a particular astronomical object, enter its name in the search field in the top-right corner, and your target will be displayed. Table 2 suggests some of the favourite objects of the *ESASky* team, for you to enjoy.

4. To see how the objects look as observed by different missions in different types of light, you have to open the 'Manage Skies' menu by clicking on the colourful button in the top-left corner of the application (Figure 4). To select an all-sky map, choose the wavelength region in the left drop-down menu, and then browse the available skies in the second menu.

5. Check if your favourite astronomical object has been observed in wavelengths other than visible light (called 'optical' by astronomers), and by which missions or surveys. Note that most maps display many blank areas, as most missions and surveys have not covered the whole sky, but only selected regions.

When you feel confident working with *ESASky*, move to the next activity.

Table 2: Some of our favourite astronomical objects.

Object	Description
M51 (Whirlpool Galaxy)	Spiral galaxy interacting with the NGC 5195 galaxy, a traditional target for first-light observations of space telescopes.
M1 (Crab Nebula)	Remnant of a supernova observed by Chinese astronomers in 1054.
M16 (Eagle Nebula)	Star forming region containing the iconic “Pillars of creation” imaged by the Hubble Space Telescope with its WFPC2 camera.
M13 (Hercules Globular Cluster)	A favourite globular cluster among amateur astronomers.
SN 1006	Another supernova remnant. It looks spectacular in X-rays!
M82 (Cigar Galaxy)	A starburst galaxy, looking very different in optical and X-rays.
Cheshire Cat	Gravitational lensing makes this cat (actually a galaxy group) smile in the HST images.
Ring Nebula	A famous planetary nebula, looks great in some of the infrared maps.
Centaurus A	A radio galaxy hosting a powerful supermassive black hole in its centre.

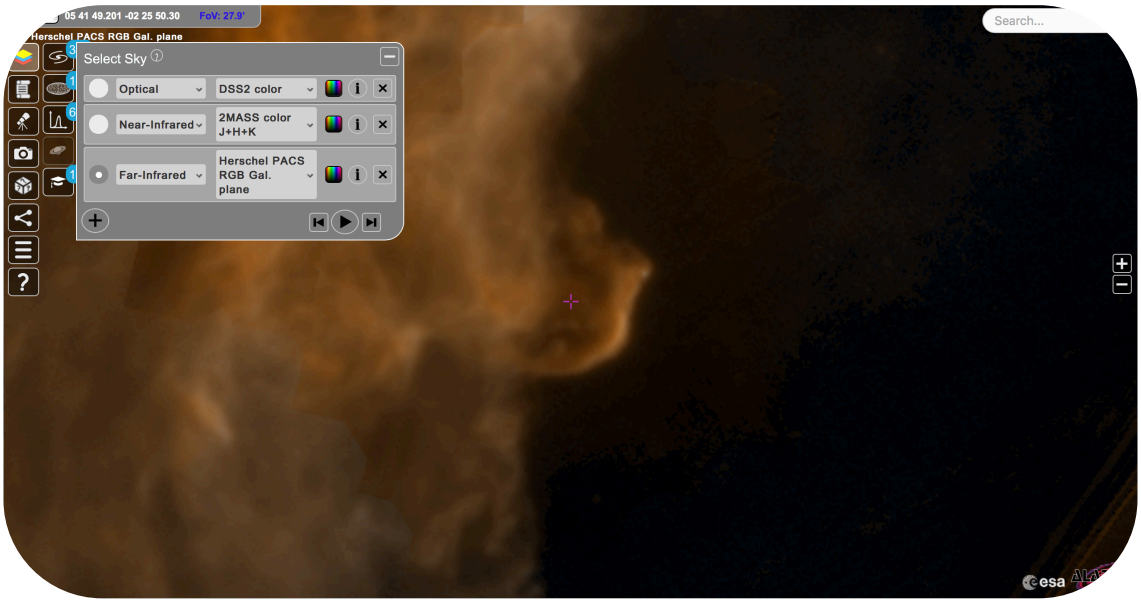


Figure 4: *ESASky displaying the Horsehead Nebula in infrared light and its Skies menu opened, showing a stack of maps. (Credit: ESA/ESDC)*

Activity 3: Empty or dark?

Now it is time to find out more about the Interstellar Medium. In this activity, you will investigate how the view of a region with large amounts of ISM changes depending on what light is observed coming from it. To observe objects or regions of space in different wavelengths of light, different types of telescopes are needed.

You will need to upload to *ESASky* a list of the regions you will study in this and the following activities.

1. Download the list of regions/objects you will study locally in your computer: ISM.txt
2. Upload the region/object list to *ESASky.* To do so, click on the Parchment button on the left-hand side, and then on 'Upload target list'. The list of regions and objects will be displayed as shown in Figure 5.
3. You can move to any region or object in the list by clicking on its name, or using the video-style buttons. The application will automatically load the image of it, and a pop-up window will provide some information about the object. The names of the objects and their descriptions are given in Table 3.

Table 3: *Sky regions to explore.*

Object	Description
Horsehead Nebula	The Horsehead Nebula is a dark cloud making part of the much larger Orion Molecular Cloud Complex. First look at the visible (optical) image: Why is it dark? Then load the near-infrared and the far-infrared maps. Are they different? Why? What do you see in each of them?
Cygnus OB2	Cygnus OB2 is an association of young massive stars (hot, blue and bright). Look at the visible (optical) image: What colour are the stars that you see? Now switch to the near-infrared, what are the differences between this image and the visible image? Can you see any evidence that the ISM is present here? How would check this?
W40	Compare this region of massive star formation with the previous region, Cygnus OB2. Check the visible (optical) image first. Do you see any evidence that the ISM is present in W40? Now inspect it in the near-infrared. What is hidden within the dust?
Sgr A*	This is the region in the centre of our Galaxy. Until the middle of the last century, this region was completely unknown to astronomers. To find out why, load the visible (optical) map, and zoom out until the field-of-view is about 12º (the size is indicated in the upper part of the screen). What does this region look like in the optical? Why was the Galactic Centre so difficult to observe? What do you expect to find if you observe it in the near and far-infrared?

4. To make a comparison between different skies (observations made of a region in different types of light), you can create a stack of maps as shown in Figure 4. To do so, open the 'Manage Skies' menu by clicking on the colourful button in the top-left corner of the application. Then click on the "+" sign and select the following maps in the drop-down menus:

   - Optical: DSS2 color
   - Near-infrared: 2MASS color J+H+K
   - Far-infrared: Herschel PACS RGB 70, 160 micron

   You can move from one map to another manually or using the video-style buttons. Clicking on the "Play" button will switch from one map to the next automatically every few seconds.

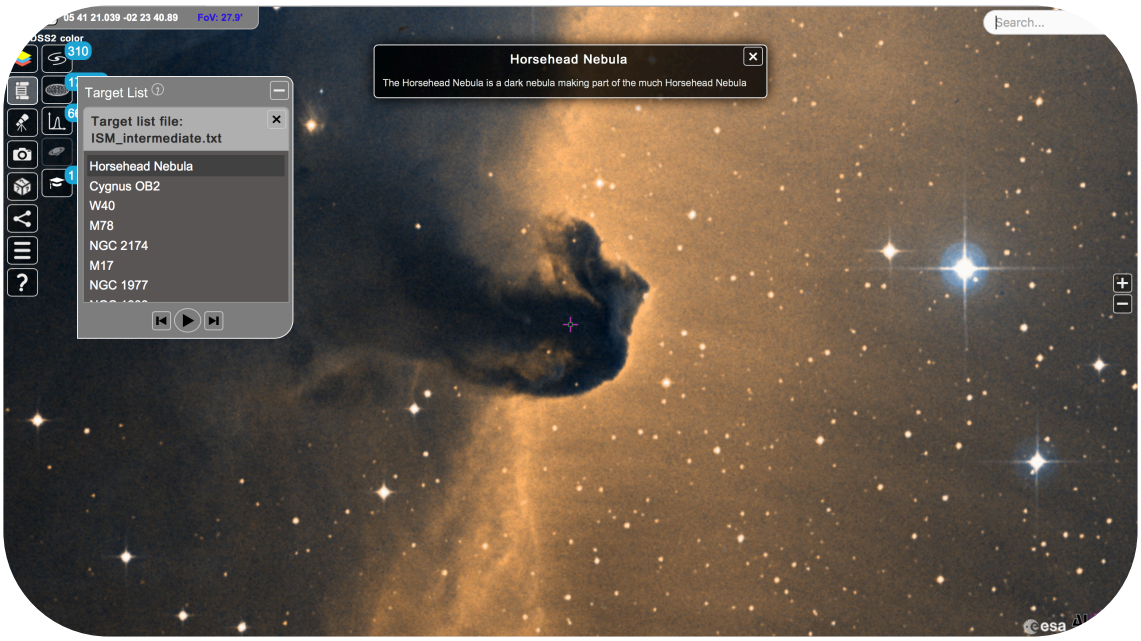


Figure 5: *The Target List functionality in ESASky, displaying the list of regions used in these activities(Credit: ESA/ESDC)*

5. Let's start by observing the ISM itself. Go to the first object in the list, the Horsehead Nebula. Look at the visible ("optical/DSS2") image (the name of the displayed map is shown above the Skies button in the top-left corner): Why are there no stars visible in the nebula? Provide a possible explanation in the box below.

6. Dust grains only absorb and scatter light whose wavelength is similar to their size; longer or shorter wavelengths are not affected and simply pass through the dust. Taking into account that the typical size of an interstellar dust grain is just a fraction of a micron (10^{-6} m), which wavelengths of light will be absorbed? Use Figure 1 to find out the answer to this question.

7. Inspect the image of the Horsehead Nebula taken by the near-infrared telescope ("near-infrared/2MASS"). Compare this image to the optical image and explain how and why they are different.

8. Taking into account that the typical temperature of interstellar dust is about 100 K, or -173 ºC, which of the three images in your stack tells you more about the properties of the ISM itself, and why? Figure 1 and Table 1 can help you find the answer to this question.

9. Interstellar gas is even colder than dust, with typical temperatures of about 10 K, or -263 ºC. According to Figure 1, which type of telescope would you need to observe this gas directly?

Activity 4: Hidden in the dust

Now you will study how the ISM is affecting the way stars are observed, by exploring the next two regions in the list, Cygnus OB2 and W40.

1. Have a look at Cygnus OB2 in the visible ("optical/DSS2") map.

   a. Do you see many stars in this image? What do they look like?

   b. The stars in Cygnus OB2 are known to be hot, massive and blue. Do the stars in the optical image look like this? If not, what could be the reason? (Hint: See Figure 2).

2. Now inspect Cygnus OB2 in the near-infrared map ("near-infrared/2MASS").

   a. Does this image look different to the optical image? Describe the differences you see.

   b. Why are some stars in the near-infrared image not seen in the optical image? Load the far-infrared map to find the answer to this question.

3. Now go to the next region, W40, and compare the images of this cluster in the three wavelength ranges.

   a. Describe the differences between the images and explain the reasons for them. (Hint: You can compare this situation with the effect of the Earth's atmosphere).

b. How would the optical image of W40 change if there were no interstellar dust? Would the stars be brighter or dimmer? Would their colour change? Explain your answers.

4. What are the names of the two effects of interstellar dust you observed in these two regions? Provide a definition for each of them.

5. Which region do you think contains more dust, Cygnus OB2 or W40? Explain your answer.

6. A light source looks dimmer the further away it is. Imagine that an astronomer is trying to measure the distance to the stars in these clusters based on their brightness in visible light images. If the astronomer did not know about the ISM, how would this affect their measurements? Would the estimated distances be bigger or smaller than the real ones? Explain your answer.

Activity 5: Unveiling the Galactic Centre

Until the advent of radio astronomy in the middle of the last century, astronomers were not able to see the centre of our Galaxy. In this activity, you will find out why.

1. Load the optical map (DSS2), switch to the last object in the list, Sgr A* (a powerful radio source near the Galactic Centre), and zoom out until the field-of-view is about 12º (the size is indicated in the upper part of the screen). Why was the Galactic Centre so difficult to observe in visible light?

2. Which type of light would you use to see the stars near the Galactic Centre? Explain your answer.

3. Is there any evidence that the ISM is present in the visible (optical/DSS2) image?

In 1922, Dutch astronomer Jacobus Kapteyn proposed that the Milky Way had a lens-shaped structure with a diameter of 30 000 light years. In his model, the Sun was positioned relatively close to the centre of the Milky Way, at a distance of 2000 light years. Kapteyn also proposed that the density of stars) decreased with distance from the Galactic Centre (Figure 6). He got these figures from counting the stars in all directions in the sky, taking into account that stars look dimmer when they are further away.

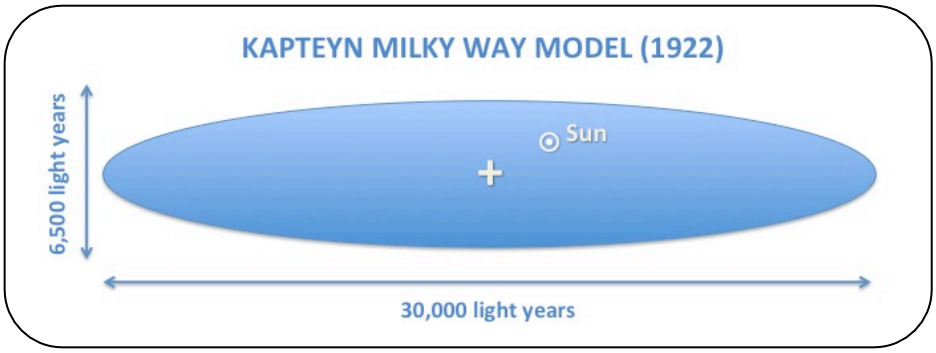


Figure 6: *Kapteyn's Galaxy model (Credit: CESAR)*

We know now that Kapteyn's model of the Milky Way is not correct. The Milky Way has a diameter of at least 100 000 light years, and the Sun is actually quite far from the centre, at a distance of about 26 500 light years. (Note: 1 light year = 9.461×10^{12} km).

4. Explain how the presence of the interstellar medium, unknown at the time, affected Kapteyn's measurements.