CESAR BOOKLET

The Interstellar Medium: What's between the stars, and how do astronomers study it?

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Introduction

Many people imagine outer space to be completely empty, but there is matter between the stars. This matter is a very diffuse mixture of gas and dust that astronomers call *the interstellar medium*, or ISM for short. Although this medium is, by several orders of magnitude, a better vacuum than any scientist can create in a laboratory, there is still about 5 to 10 billion solar masses of gas and dust out there, comprising about 5% of the mass of visible stars in our Galaxy.

What is the ISM made of? What are its properties? And how can we tell it is there? To answer these questions, we first have to review the way astronomers gather information about the Universe –by studying the light from astronomical objects that reaches Earth.

The electromagnetic spectrum

The colours of light

You have surely seen a rainbow, and you are probably familiar with the explanation to this phenomenon: In very basic terms, sunlight is refracted as it gets through water droplets suspended in the Earth's atmosphere. Because white light is a mixture of six (or seven) different colours, and each colour is refracted a different angle, the result is that the colours get arranged in a given order, from violet to red through blue, green, yellow and orange. We can get the same effect in a laboratory by letting light go through a prism, as shown in Figure 1. This arrangement of colours is what we call a *spectrum*.

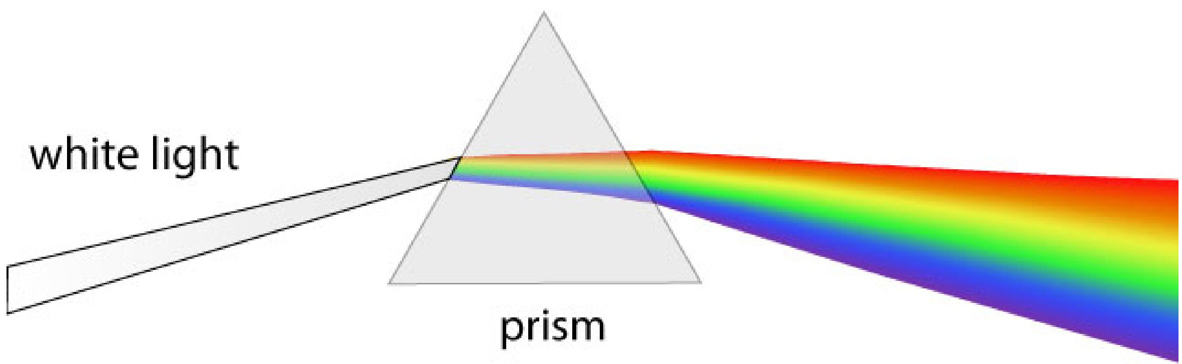

Figure 1: *White light passing through a prism creates a rainbow.* ***Credit:*** *physics.stackexchange.com*

Yet the spectrum of light is not only made of the colours we see with our eyes. There are other colours that are invisible, although they can be detected with the appropriate devices. Beyond the violet, we have ultraviolet, X-rays and gamma rays. On the other extreme, beyond the red, we have infrared and radio. Although we cannot see them, we are familiar with these other types of light: for example, we use radio waves to transmit music from one station to our car receiver, ultraviolet light from the Sun makes our skin get tanned, X-rays are used by radiography machines to check if we have a broken bone, or we change channel in our TV device by sending an infrared signal to it from the remote control.

Physicists describe light as something called *electromagnetic radiation* or *electromagnetic wave*. The word *radiation* means ‘energy that is transported from one spot to another without need of direct contact between the two locations’. Light in each of these colours carries a different amount of energy: gamma rays are the most energetic, and radio is the least. Thus, when we observe gamma or X-rays from an astronomical object, we know that something really powerful is happening there. This energy is transported in the form of a wave, and each colour is related to a different wave size: The more energy the wave carries, the narrower it is –or, in technical terms, the shorter its *wavelength*. Hence, X-rays have shorter wavelengths than visible-light waves (also called ‘optical waves’ in Astronomy), and visible light has shorter wavelengths than radio waves.

Also, the amount of light of a given colour that is emitted by a body depends on its temperature. Contrary to what everyday experience tells us, though, most of the light emitted by the hottest objects in the universe has a colour on the ‘blue side’ of the spectrum (violet and ultraviolet), while the coolest objects emit most of their light in a colour in the ‘red side’ of the spectrum (infrared and radio). In other words, a blue star is hotter than a red star! (Note, however, that we are talking about the light that an object *emits*, and not the light it *reflects*. We see most of the things around us thanks to the light they reflect, because the light emitted by them has a colour that our eyes cannot detect.)

Figure 2 summarises the properties of the electromagnetic spectrum:

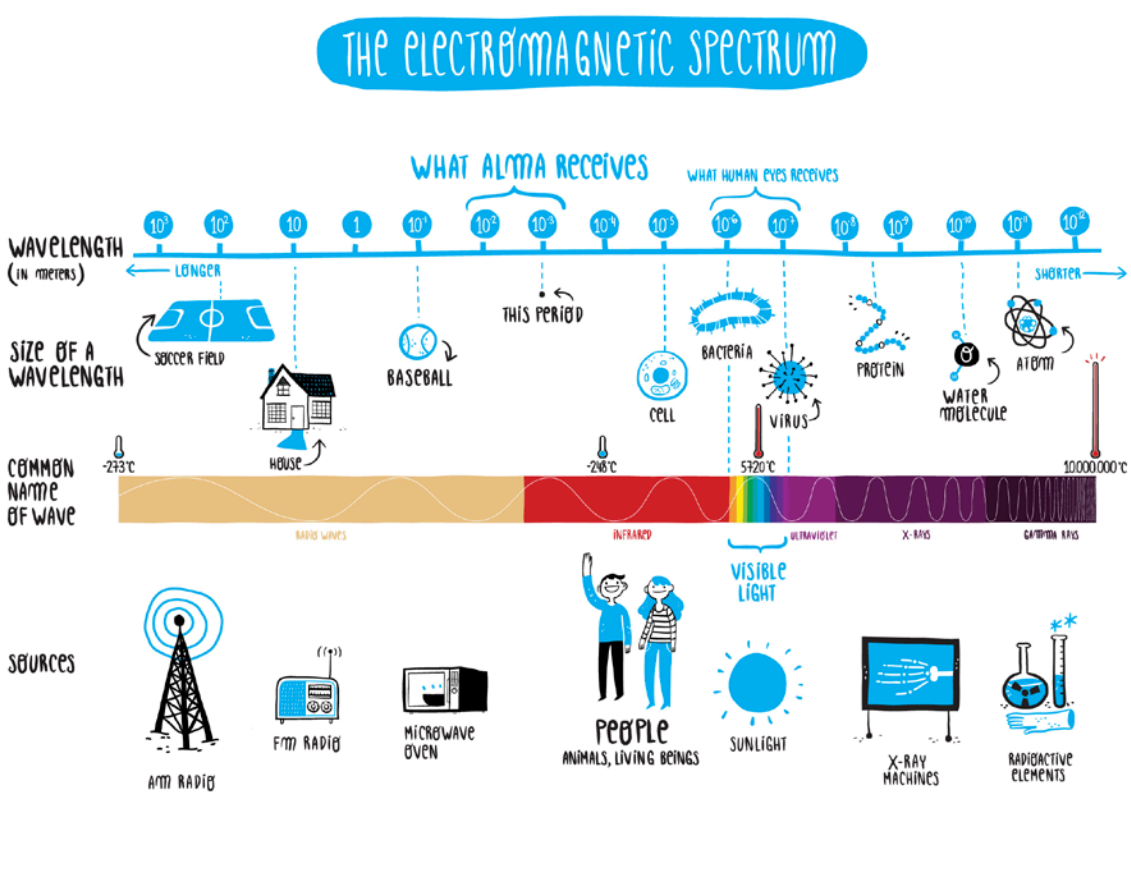

Figure 2: *Properties of the electromagnetic spectrum.* ***Credit:*** *ESO/ALMA*

Observing across the spectrum

Because astronomical objects emit light in different colours depending on their temperature and the phenomena that are going on in them, it is important to observe them in different types of light to fully understand them. As an example, Figure 3 shows the Crab Nebula, a supernova remnant about 6,000 light-years from Earth, observed by different telescopes that detect different types of light. Note how the appearance of the nebula changes depending on the wavelengths that are observed, because they are being emitted by different components or phenomena in this object. The cool gas and dust dominate the emission in the radio and infrared bands, respectively; in visible and ultraviolet light, we see the gas heated and ionised by the central neutron star (all that is left from a massive star that exploded at the end of its life); and X and gamma-rays reveal the emission from the neutron star itself, which is surrounded by a disk of very hot gas in the X-ray image.

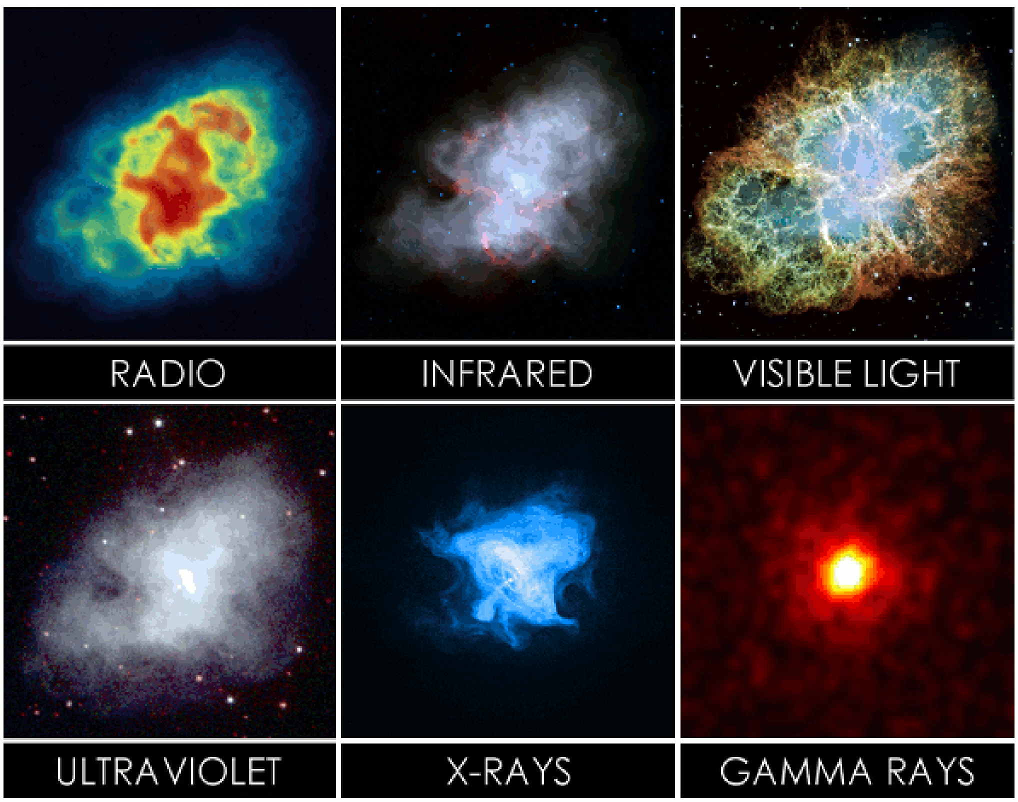

Figure 3: *The Crab Nebula observed across the electromagnetic spectrum.* ***Credits:*** *NASA/ESA/NRAO*

In Table 1, you have a list of the temperatures of sources emitting in the different colours of the electromagnetic spectrum, as well as some examples of these sources.

But observing across the full electromagnetic spectrum is not possible from Earth, as the atmosphere blocks most of the invisible light. For this reason, telescopes observing the universe in invisible colours (except part of the radio and infrared) must be placed in space. Figure 4 shows the space telescopes operated by ESA, and the part of the electromagnetic spectrum they observe.

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

Type of radiation	Temperature	Typical sources
Gamma-rays	$>10^8$ K	Matter falling into black holes
X-rays	10^6-10^8 K	Gas in clusters of galaxies Supernova remnants Stellar coronae
Ultraviolet	10^4-10^6 K	Supernova remnants Very hot stars
Visible	10^3-10^4 K	Stars Hot planets
Infrared	10-10^3 K	Very cool stars Planets Cool clouds of dust
Radio	<10 K	Cool clouds of gas The Cosmic Microwave Background (CMB) Electrons moving in magnetic fields

Adapted from: *NASA/Imagine the Universe!*

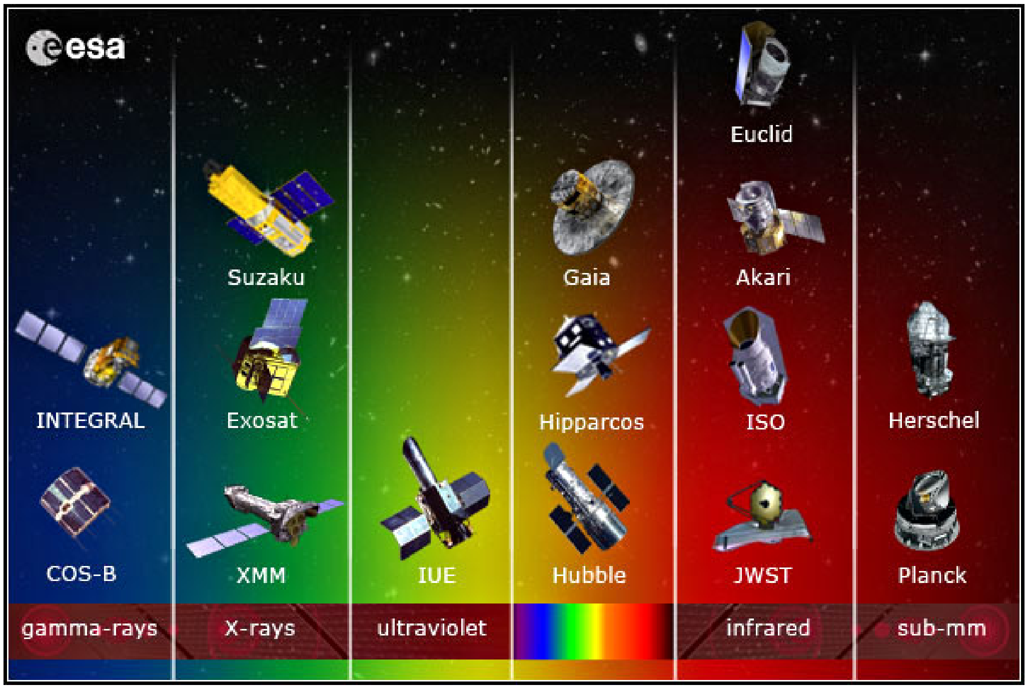

Figure 4: *ESA's fleet of telescopes across the electromagnetic spectrum. (The sub-millimetre range corresponds to the shortest radio waves.)* ***Credit:*** *ESA*

The Interstellar Medium

Interstellar gas and dust

The Interstellar Medium (ISM) is the material filling the space between the stars. It consists mainly of gas (99%) and dust (1%), mostly found in the form of clouds, or *nebulae* (plural of *nebula*).

About 75% of the interstellar gas is in the form of hydrogen, and nearly all the remaining 25% as helium. This gas is extremely cold (around 10 K) and dilute, about 1 atom per cubic centimetre (for comparison, the air we breathe has a density of about 30,000,000,000,000,000,000 molecules per cubic centimetre). However, despite this very low density, the amount of matter adds up over the vast distances between two stars.

Interstellar dust is not like the dust you might find under your bed. It consists mainly of silicates, iron, carbon and ice. Dust particles are irregularly shaped and very small, just a fraction of a micron across (similar to the wavelength of blue light), and have typical temperatures of around 100 K.

Observing the ISM

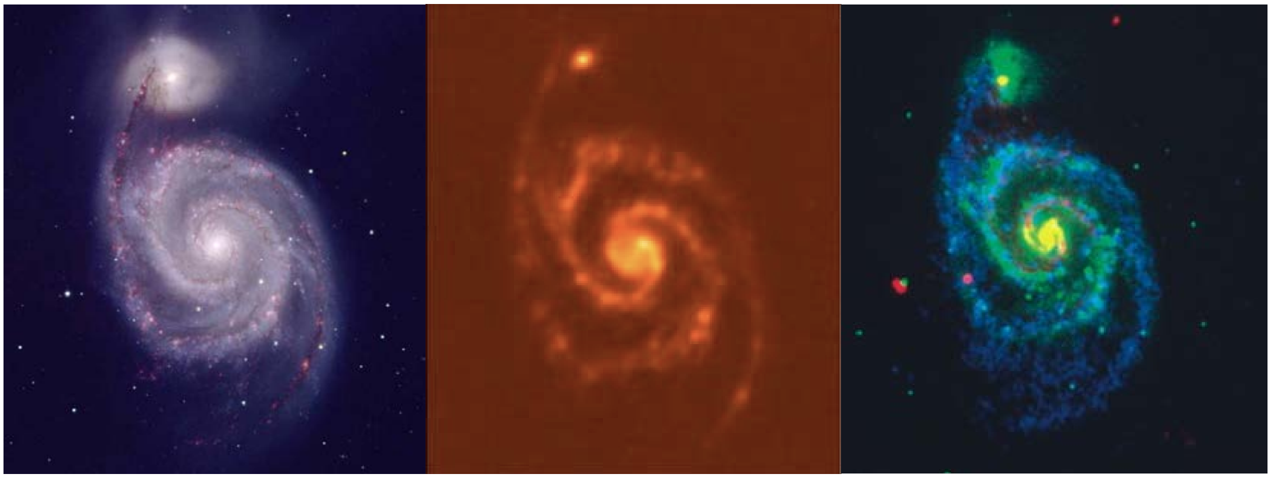

Figure 5: *M51, the Whirpool Galaxy, observed in visible light (Hubble Space Telescope, left), far-infrared (Herschel, centre) and radio (NRAO, right).* ***Credits:*** *ESA/NASA/NRAO*

Figure 5 shows an example of how astronomers study the ISM using invisible light. Because of its really low temperature, interstellar gas emits light in the radio band of the electromagnetic spectrum. Thus, we can tell that the spiral arms of the Whirpool Galaxy contain lots of gas because they are nicely seen in the radio image.

Dust is hotter than gas. Bodies of this temperature (about 100 K) mainly emit far-infrared light (light with very long wavelengths), and therefore, dust is a favourite target for infrared observatories. The infrared image of the Whirpool Galaxy shown in the central panel of Figure 5 tells us that the spiral arms contain large amounts of dust as well.

Figure 6: *Types of nebulae: emission (Orion Nebula, left) and reflection (Pleiades, right).* ***Credits:*** *AAO/ROE*

However, if they become gravitationally unstable, ISM clouds can collapse and form stars that, in turn, heat up the surrounding gas, which glows with pinkish or reddish colour, and is thus observable in visible light. This type of glowing cloud is called an *emission nebula*; an example of this type of nebula is shown in the left panel of Figure 6.

Dust can also be noticed at visible wavelengths because of the effects it has on the light from the stars located within or behind it. If the dust is thick enough, the light will be completely blocked, leading to dark areas: we will see a dark cloud, as the one shown in the left panel of Figure 7. The reason is that, as explained above, the dust grains have sizes approximately matching the wavelengths of visible (blue) light; slightly longer wavelengths, in the near-infrared range of the spectrum, do make it through the cloud, as shown in the right panel of Figure 7.

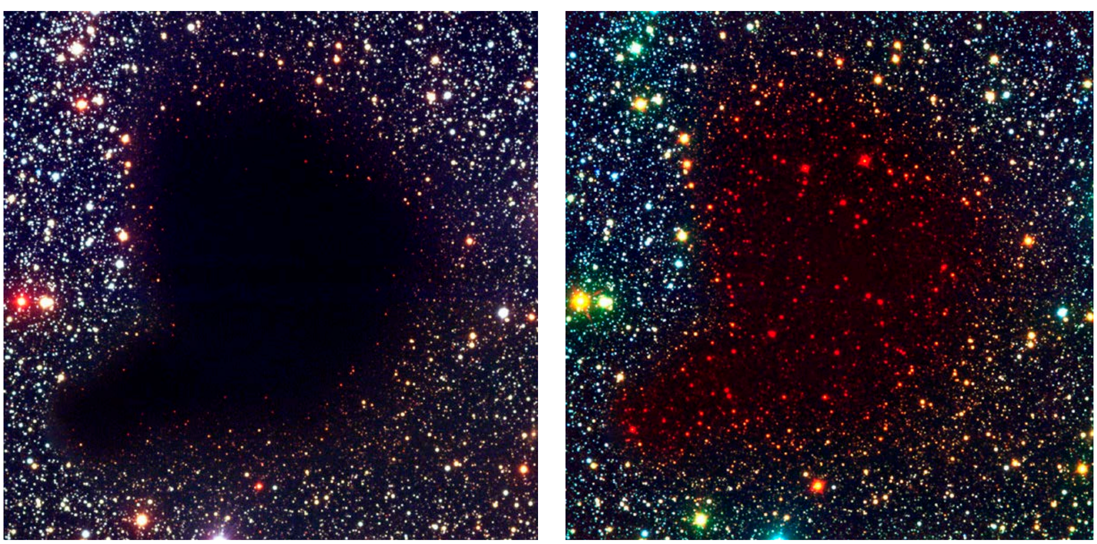

Figure 7: *The left panel shows Barnard 68, a dark cloud, as it is observed in visible light. The right panel shows the image in the left combined with a near-infrared image of the same cloud, where the stars hidden in the dust are unveiled.* ***Credits:*** *ESO*

Even if the dust does not completely block the visible light, part of it will be absorbed and scattered, and the star will look dimmer than expected just by its distance, a phenomenon known as *extinction*. Blue light will be more scattered than red light, and as a consequence, the star will also look redder than it really is, an effect known as *interstellar reddening*. This process is similar to those that make the Sun red at sunset.

On the other hand, we may also see the blue light that is being scattered –reflected– by the dust. The phenomenon is similar to the one causing the sky look blue. A cloud that is reflecting blue light will also look bluish; this is what we call a *reflection nebula*. An example of this type of nebula is shown in the right panel of Figure 6.

The effects of extinction and reddening are illustrated in Figure 8. It is important for astronomers to keep them in mind when studying astronomical objects, because otherwise, they may think that these objects are farther away and cooler than they really are, and get wrong conclusions about them.

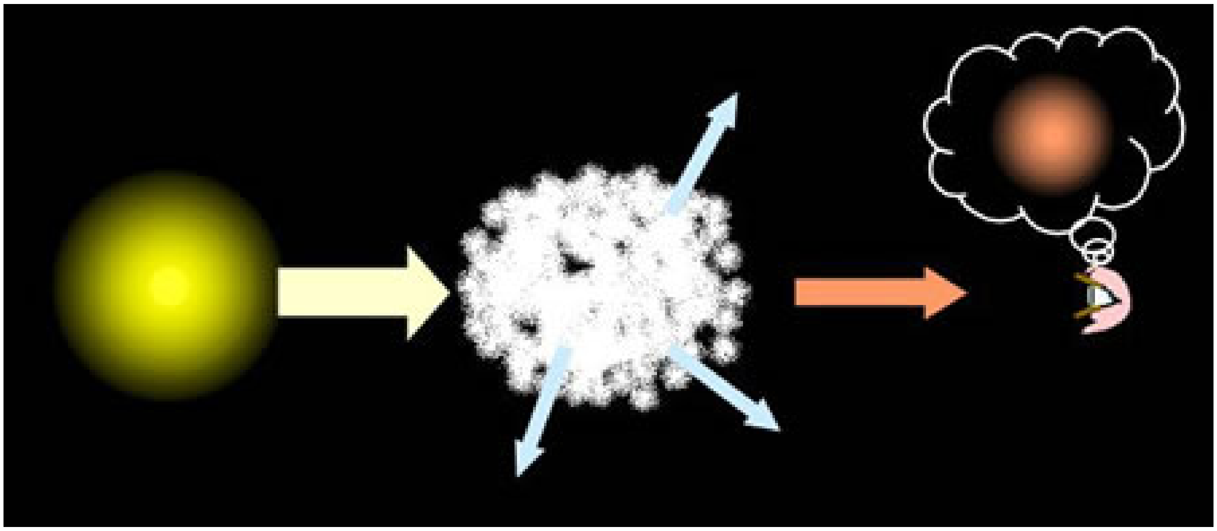

Figure 8: *Dust grains along the line of sight scatter and absorb blue light and let red light get through. The object behind the dust will look redder and fainter than it really is.*
Credit: *COSMOS, the SAO Encyclopedia of Astronomy*

References

- Astronomy Notes by N. Strobel: http://www.astronomynotes.com
- Cosmos, the SAO Encyclopedia for Astronomy: http://astronomy.swin.edu.au/cosmos/
- Imagine the Universe!: https://imagine.gsfc.nasa.gov/science/toolbox/toolbox.html
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