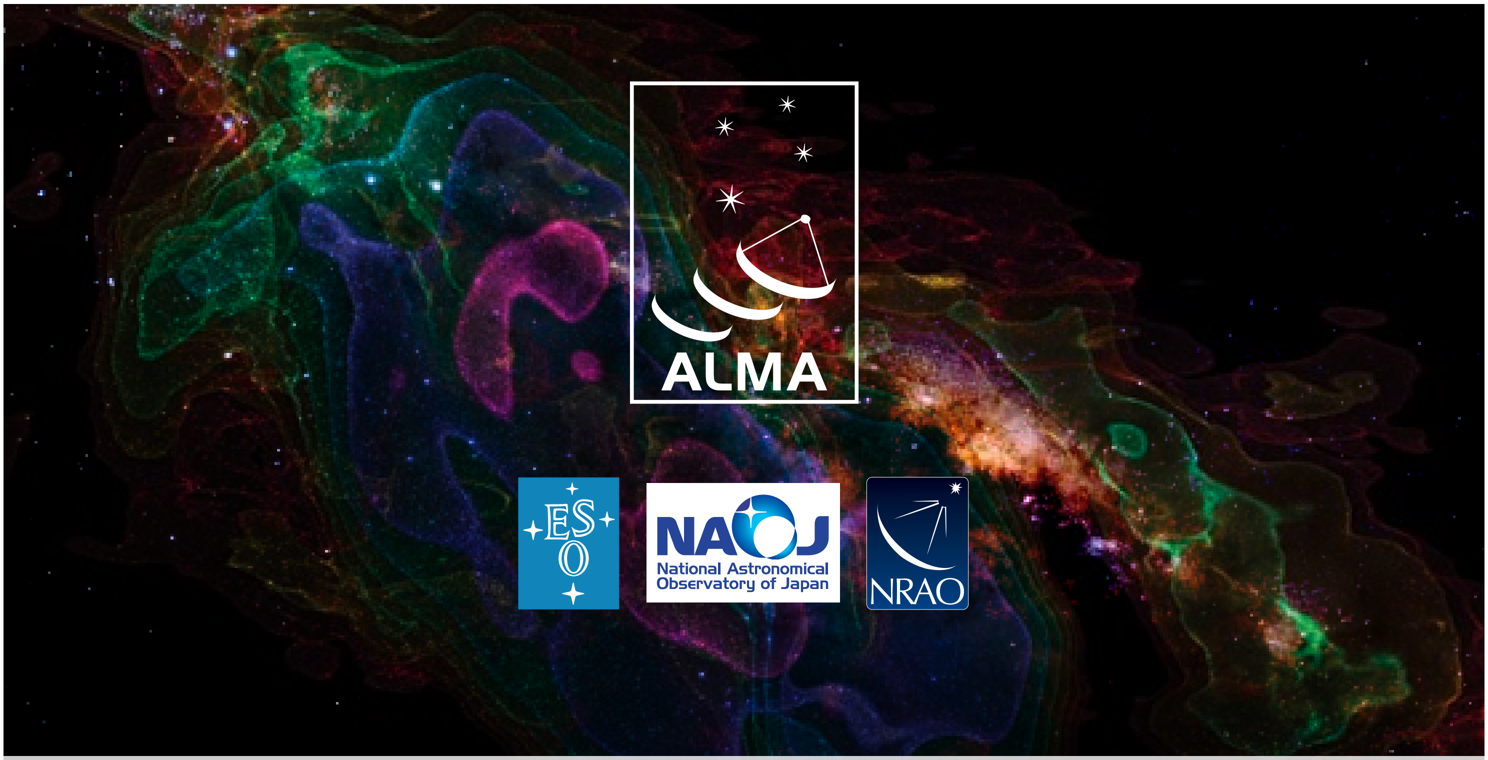

RADIO ASTRONOMY MANUAL

ALMA at School

Contents

The words highlighted in the text are defined may be found in the glossary at the end of the manual.

Cover image
Composition: Colorful view of ALMA. Credit: ESO/B. Tafreshi; three-dimensional view of gas outflow from NGC 253 as seen by ALMA. Credit: ALMA (ESO/NAOJ/NRAO)/Erik Rosolowsky

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Based on: “The Invisible Universe” from Universe Awareness (UNAWE) and “Exploring Our Cosmic Origins - Educational Material about ALMA” from the European Southern Observatory (ESO)
Translation: Kora McNaughton

Prologue

Since the beginning of time, human beings have been fascinated by the sky and stars. However, it was only with the invention of the telescope in 1609 that humans could begin to study astronomical objects in detail, transforming astronomy and taking discoveries to unprecedented levels thanks to technological progress.

Today we can study the Universe by observing types of radiation, different from visible light. Radio waves –including infrared, gamma rays, ultraviolet and X-rays– provide astronomers with glimpses into a completely new world: the "invisible" Universe.

It will take many more generations of astronomers to reveal all of the secrets of the Universe. That's why it is so important for the future of astronomy, and for science in general, to spark the interest of children and assist teachers in guiding their learning.

This manual is designed primarily for teachers who want to expand their knowledge about radio astronomy in general and the ALMA Observatory in particular. It also contains activities that can be used in the classroom or as part of an extracurricular workshop. Although the manual provides recommendations for using the material in courses and grade levels, teachers should use their own judgment to determine how to integrate it into their planning, based on their knowledge of their students and their schools' curricular plans.

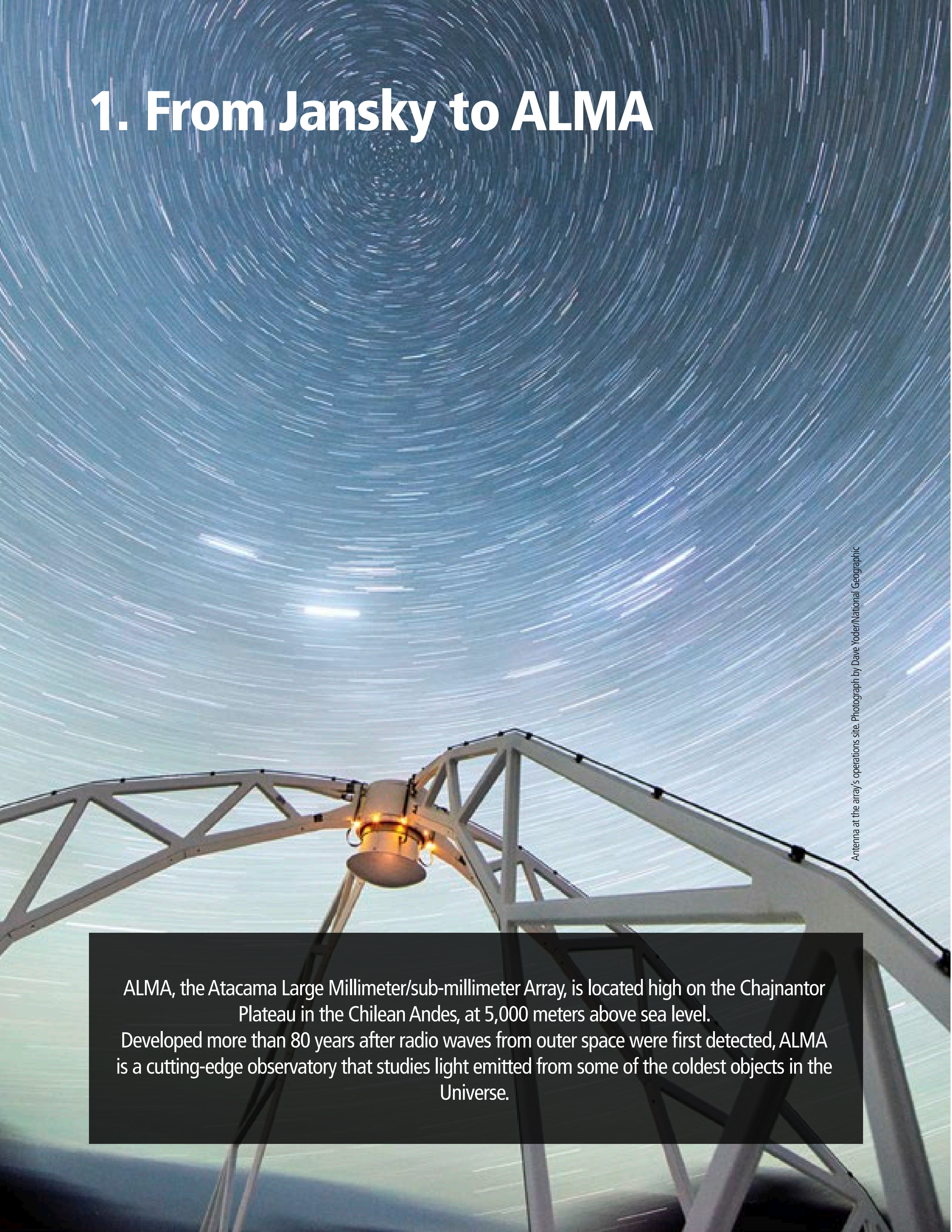
The text is organized into four chapters. The first provides a brief history of radio astronomy and general aspects of its physical properties, in comparison to optical telescopes. The second chapter contains a deeper examination of the physical concepts underlying radio astronomy such as refraction, reflection, resolution power and others, in order to help students understand the implications for observation. The third chapter explores the areas of radio astronomy investigation that ALMA can address and some conclusions that are expected to be verified. In other words, this chapter contains a brief description of the state of the art in radio astronomy research.

Finally, the fourth chapter contains a series of activities for working with students. The activities are organized by level of complexity, starting with the simplest ones and ending with more in-depth activities, all of which are related to the ideas described in the previous chapters. The manual also provides recommendations on using the activities in natural sciences courses at different grade levels.

This manual assumes that teachers have a basic understanding of concepts of physics, chemistry and algebra, and therefore does not explain elementary concepts that can be found in any science book. Nevertheless, some of these concepts have been included in the glossary for quick reference.

Nor is the manual aimed at covering topics in depth or providing more complex technical details or theoretical models. Rather, it is designed to introduce these subjects and contribute a set of teaching activities as a first step. At the end of each chapter there is a set of questions to help students reflect on and understand what they have read.

1. From Jansky to ALMA



Antenna at the array's operations site. Photograph by Dave Yoder/National Geographic

ALMA, the Atacama Large Millimeter/sub-millimeter Array, is located high on the Chajnantor Plateau in the Chilean Andes, at 5,000 meters above sea level.
Developed more than 80 years after radio waves from outer space were first detected, ALMA is a cutting-edge observatory that studies light emitted from some of the coldest objects in the Universe.

1.1 Jansky’s Observations

It can take a long time to get to ALMA, not just because its location is almost inaccessible to human beings–at 5,000 meters above sea level and in the middle of the driest desert in the world–but also because it represents an enormous advance in this area of astronomy that observes the invisible. It is truly a milestone in radioastronomy.

This journey began almost accidentally in 1931, when Karl G. Jansky, an engineer from the United States, made his first observations of extraterrestrial radio sources. During those years, Bell Labs had commissioned Jansky to study possible uses for short wave bands in communication, and needed to evaluate potential interference in the atmosphere. Using an antenna he designed and built himself, Jansky began receiving radio waves generated by natural sources such as electrical storms and lightning.

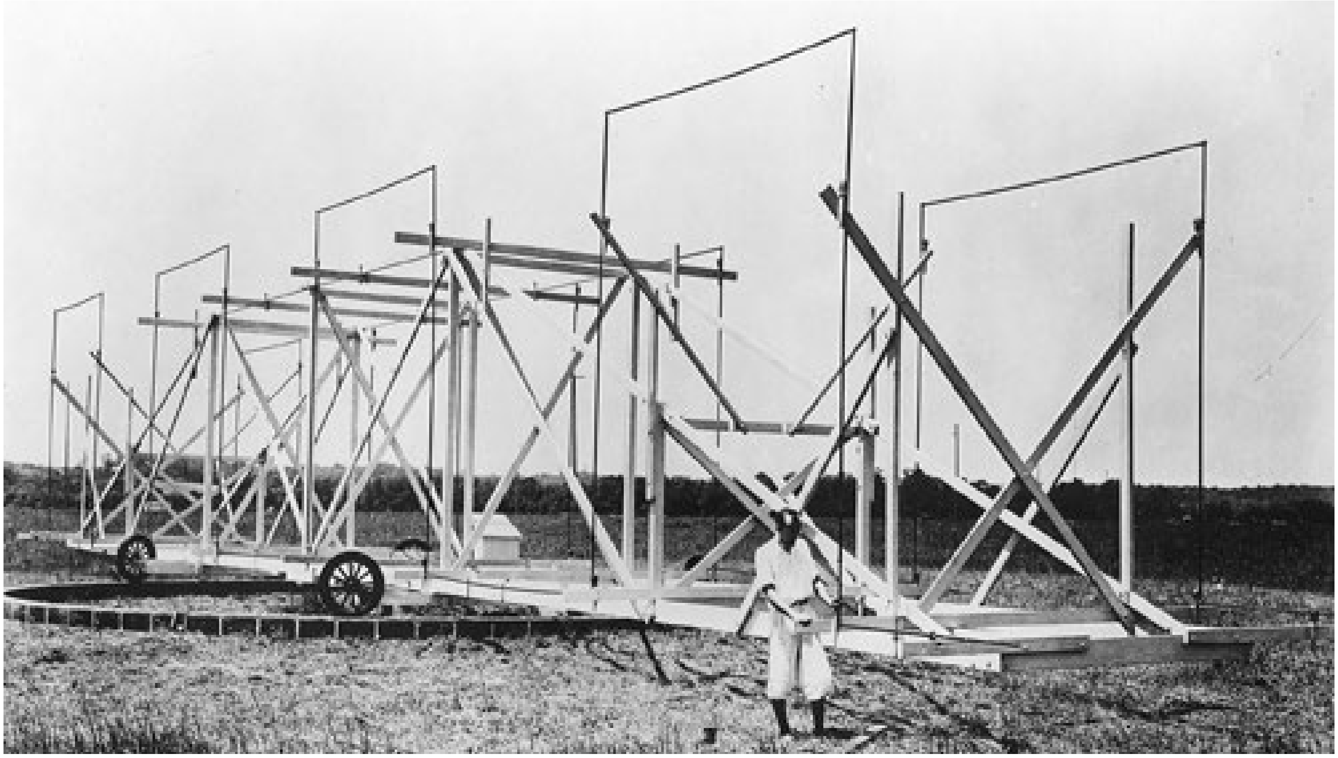


Image 1. Jansky’s merry-go-round antenna. The wheels were used to rotate the structure and point it in different directions. The antenna was designed to receive waves with a frequency of 20.5 MHz (1 MHz=106 Hz) and a wavelength of approximately 14.6 meters, located in the shortwave (SW) band. In comparison, an FM radio can tune in waves from 88.0 to 107.0 MHz (3.4 to 2.8 meters, respectively). Credit: NRAO-Green Bank.

The antenna was mounted on a rotating platform that could detect radio signals from any direction. Close to the antenna structure was a shed where Jansky kept a “pen and paper” recording system–similar to a seismograph–with which he recorded signals from nearby storms, distant electrical storms and a constant yet weak signal of unknown origin. Over the several months during which he recorded data, the unknown signal was always present. Jansky’s process consisted of rotating the antenna one full turn (360º) over 20 minutes. Thus, in one hour the antenna pointed in the same geographic direction three times. Image 2 shows one of the records of the signal over a two-hour period.

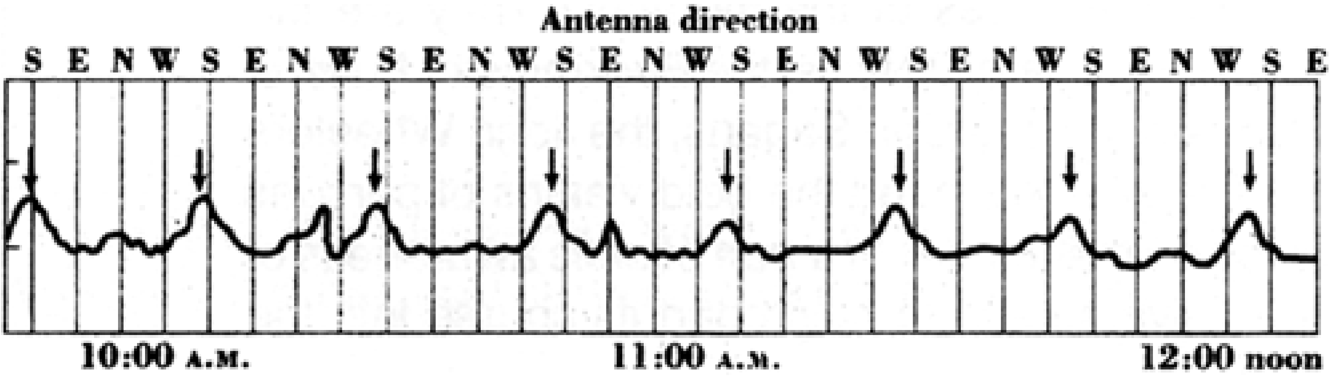


Image 2. Part of what Jansky recorded in February 1932. The geographical direction is indicated at the top: south (S), east (E), north (N) and west (W). The time is indicated on the bottom. Each vertical division marks a period of five minutes. The arrows point to the crest or maximum observed every 20 minutes, as the antenna swept across the plane of our galaxy.

Jansky initially believed the sun was the source of the unidentified signal, but as the days passed, he saw that the appearance of the crest was delayed by almost four minutes each day (see note on the difference between a solar and a sidereal day). This time difference led Jansky to conclude that the source emitting these radio waves was located in the Milky Way, whose greatest intensity was in its central zone, in the Sagittarius constellation.

This discovery was widely disseminated in the press, including a report in the New York Times published on May 5, 1933. Jansky intended to continue with his measurements to investigate these sources from outer space, but Bell Laboratories did not consider the signals to be a problem and he was assigned to another project, leaving this task to future astronomers. The unit of spectral flux density, in the International System, is now known as the Janksy.

Note on the difference between the solar day and the sidereal day

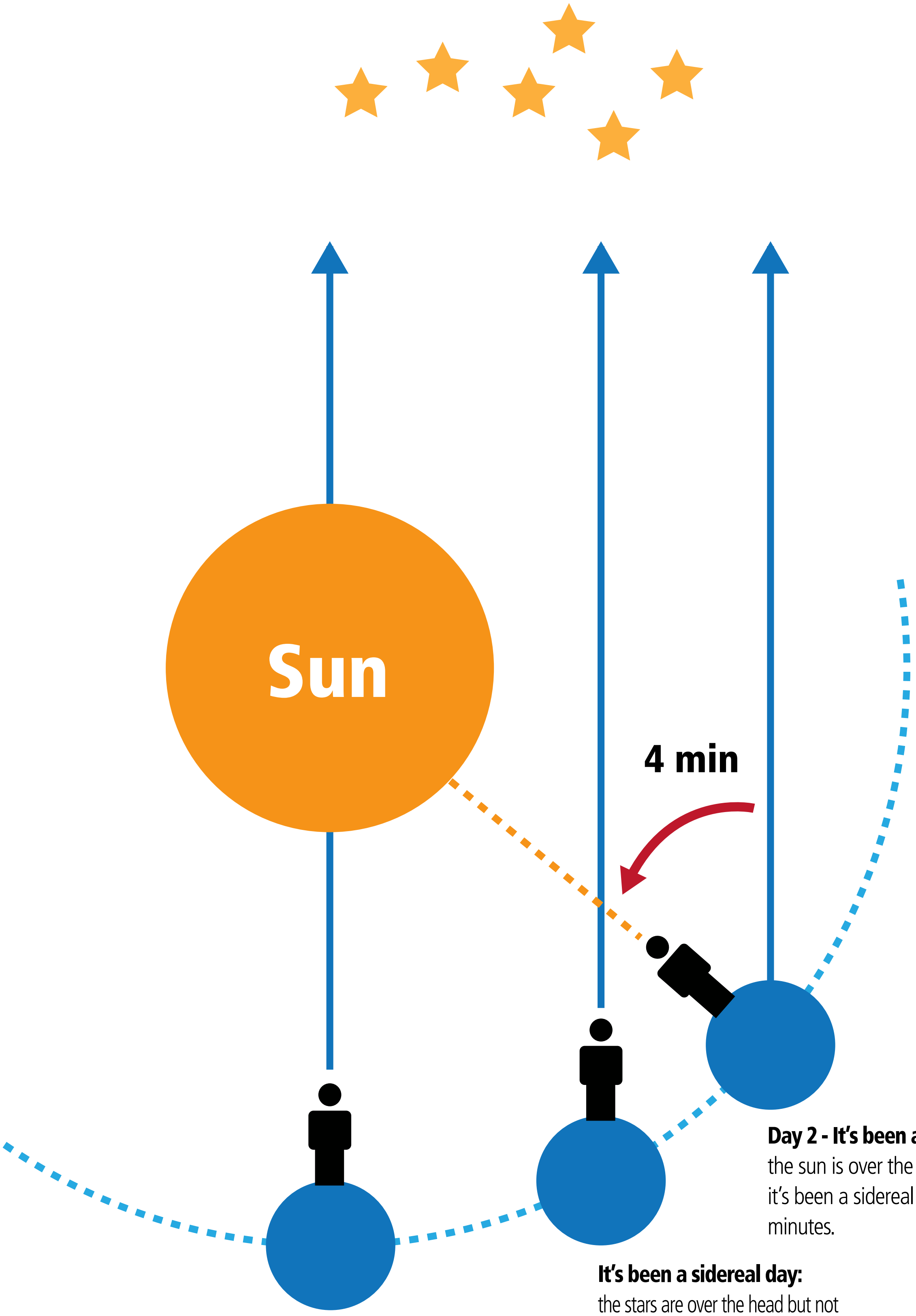
The definition of day seems simple: It is the time it takes a planet, satellite, or celestial body to complete a rotation around its axis. However, to describe the movement of a body we need a system of reference, that is, something with respect to which we can say that a certain celestial body has completed a rotation, or more generally, that it moved. If we say the Earth rotates on its axis, with respect to what point can we say that it has completed a rotation?

This leads us to two definitions: the solar day and the sidereal day. The former is based on the measure of time of the Earth's rotation with respect to the Sun and the latter is with respect to the stars.

The solar day is the time between midday on one day to midday on the following day. When we say "midday," we are referring specifically to the time in the day when the Sun reaches its maximum height in the sky. This is also expressed as the time at which the Sun passes the celestial meridian (am and pm in the 12-hour system: ante meridian and post meridian).

But the Earth's orbit around the Sun is elliptical, at a speed that varies during the year. As a result, the amount of time between two middays is never the same. To simplify this situation, assume that there is an imaginary Sun, with respect to which the Earth orbits in a circular pattern at a constant speed. That speed is its average speed in the elliptical orbit, resulting in a solar day of 24 hours.

The Earth's revolution around the Sun is also the reason why the sidereal day (which is measured with respect to the stars) is approximately 4 minutes shorter than the solar day, resulting in a sidereal day of 23 hours and 56 minutes. The following image provides a comparison of both.



Day 2 - It's been a solar day: the sun is over the head, but it's been a sidereal day and 4 minutes.

It's been a sidereal day: the stars are over the head but not the Sun.

Day 1: the Sun and stars are over the head.

Image 3. Diagram representing the difference between the sidereal day and the solar day.

1.2 The First Radio Telescopes

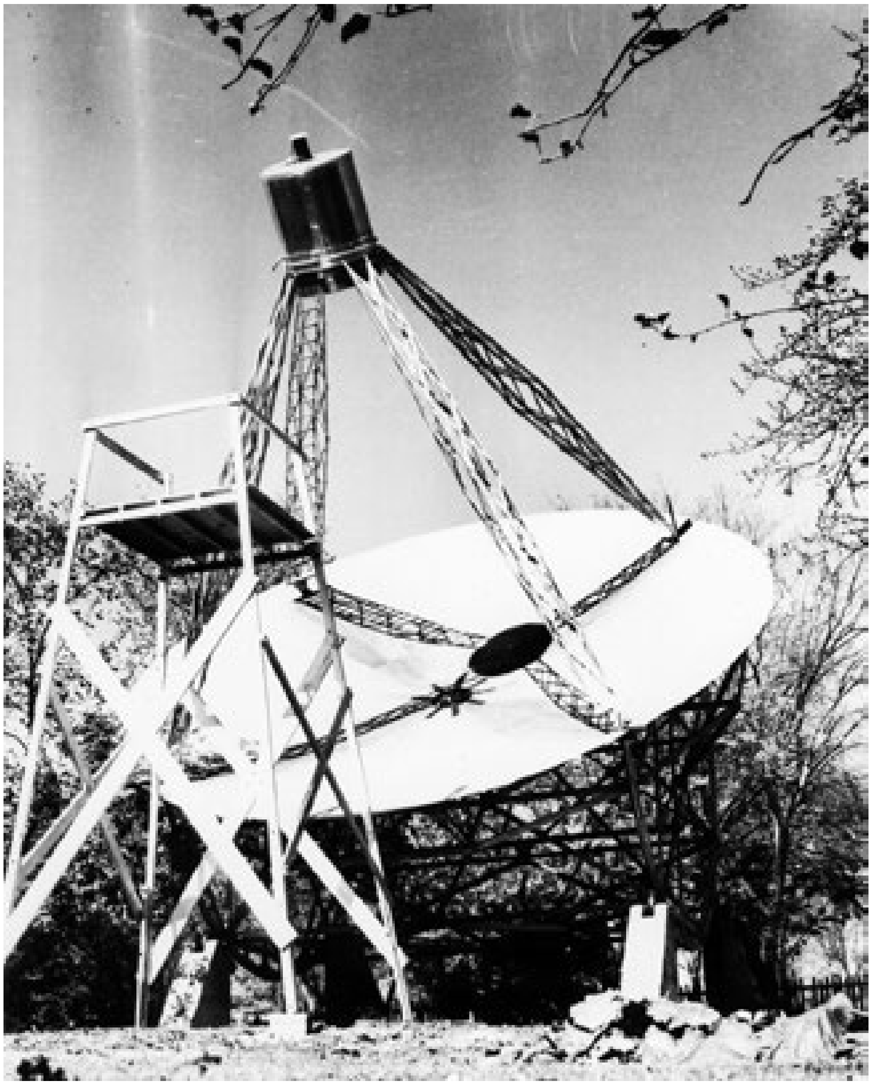


Image 4. First radio telescope built by Grote Reber in 1937. Credit: NRAO-Green Bank.

Fortunately, there were many scientists interested in continuing the work Jansky had started, notably Grote Reber, an engineer from the United States who in 1937 built a homemade radio telescope in his backyard (see Image 4).

In the early 1960s, the largest radio telescope was at the Jodrell Bank Observatory, with a diameter of 76 meters. This was later joined by the gigantic RATAN-600 radio telescope in Russia, with a diameter of 576 meters, and the Arecibo telescope in Puerto Rico, with a diameter of 305 meters.

Years later, British astronomer Martin Ryle developed the technique known as interferometry, which uses several radio telescopes located far apart to capture radio waves, as if they were one large telescope. This procedure led to the discovery in 1968 of the first pulsar.

Over time and with technological progress, gigantic radio telescopes were replaced by radio telescope arrays complemented by interferometry systems such as the Very Large Array (VLA) in New Mexico with 27 antennas and ALMA, which was inaugurated in 2013 and is now the largest and most modern array in the world.

1.3 Basic Elements of the ALMA Radio Telescope

The most visible part of a radio telescope is its reflector dish (see Image 5). At ALMA, most of the reflectors have a diameter of 12 meters. Each reflector performs the same function as a mirror in an optical telescope: capturing radiation from distant astronomical objects and directing it towards a receiver that measures the levels of that radiation.

What distinguishes the two telescopes is the wavelength of the radiation absorbed: An optical telescope captures visible light while a radio telescope like ALMA captures radio waves.

Image 5. Array of 13 antennas on the Chajnantor Plateau. Credit: ESO.

As we will see later, visible light is just a small part of the electromagnetic spectrum and can be observed by the human eye. Radio waves, on the other hand, belong to a broader group of waves, such as those captured by a common FM radio. At ALMA, the waves detected are known as millimeter and sub-millimeter radiation, since their wavelengths are within that range of measurement (from millimeters to thousandths of a millimeter).

Image 6 shows clearly one of the main differences between the antenna of a radio telescope and the primary mirror of an optical telescope.

Both an optical telescope and an ALMA antenna have a parabolic surface to collect the waves to be studied (visible waves and radio waves, respectively). Their appearance differs in terms of the material covering the parabolic surfaces: in an optical telescope, components similar to mirrors are used, while an ALMA antenna uses panels that reflect the radio waves in a highly efficient way.

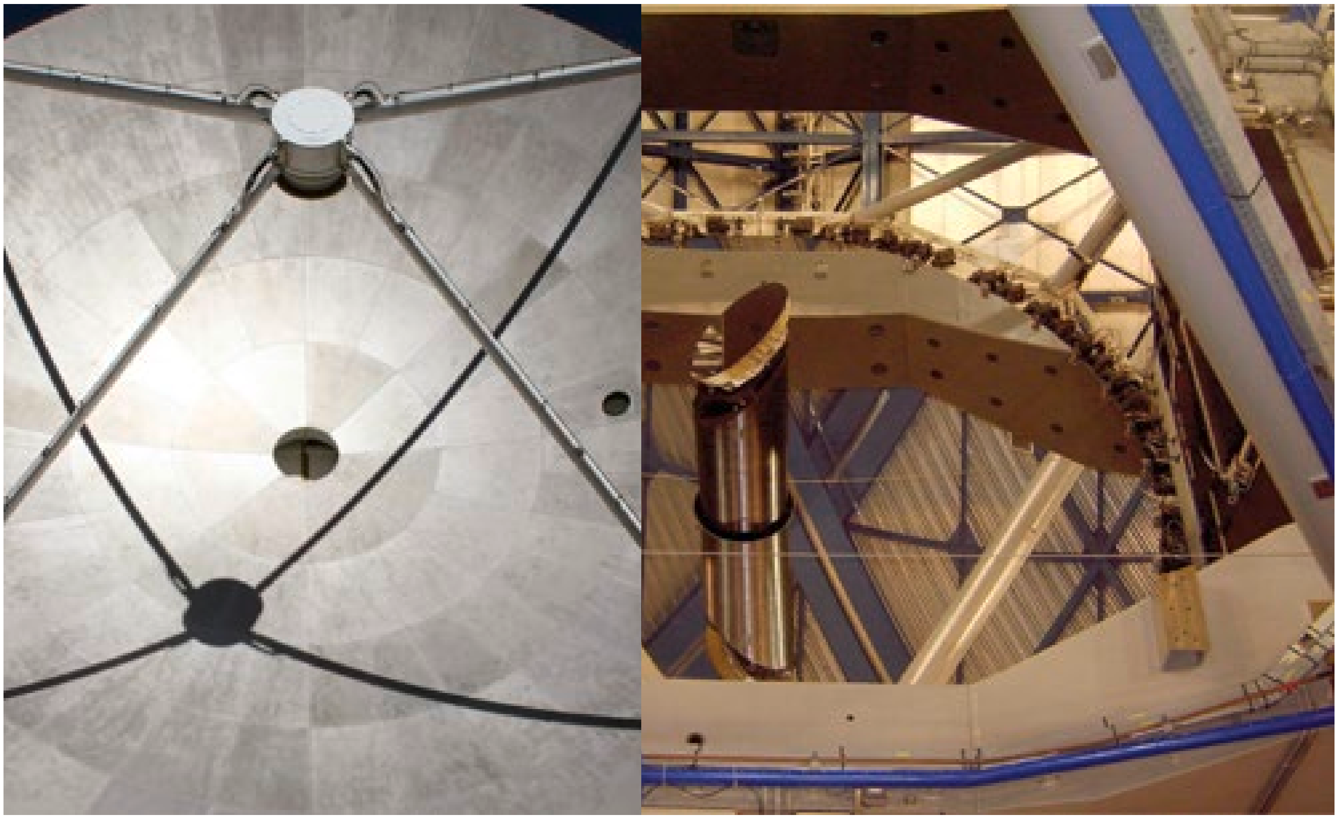


Image 6.
Detail of the dish of an ALMA antenna (left) and the primary mirror of one of the VLT optical telescopes (right). Credits: ALMA (ESO/NAOJ/NRAO) (left); Pablo A. Torres (right).

In both cases the reflective surfaces must be practically perfect, since any imperfection will prevent the telescope from correctly obtaining data. In addition, the motorized mechanism that moves the antenna must be extremely precise to aim it at the celestial object being studied. For example, ALMA can accurately aim at the position of both poles of a golf ball located 15 kilometers away.

1.4 How Images are Formed by a Radio Telescope

When you think of an optical telescope, it's easy to understand how it forms an image. With both refracting and reflecting telescopes, the light is conducted by the various optical elements (lenses on the former and mirrors on the latter) to the lens, which is what we look at, either with our eyes or with a photographic camera.

But how are images formed from radio waves that we can't see with our eyes? The process is somewhat more complex. First, radio telescopes capture radio waves coming from the Cosmos, that are reflected on the surface of the dish, which thanks to its parabolic shape, concentrates the waves on a focal point. At this focal point a receiver takes in, amplifies and digitalizes the radio waves, so that the information they provide–which includes the intensity of the waves and the exact position of the point in the Universe that they come from–can be converted into images.

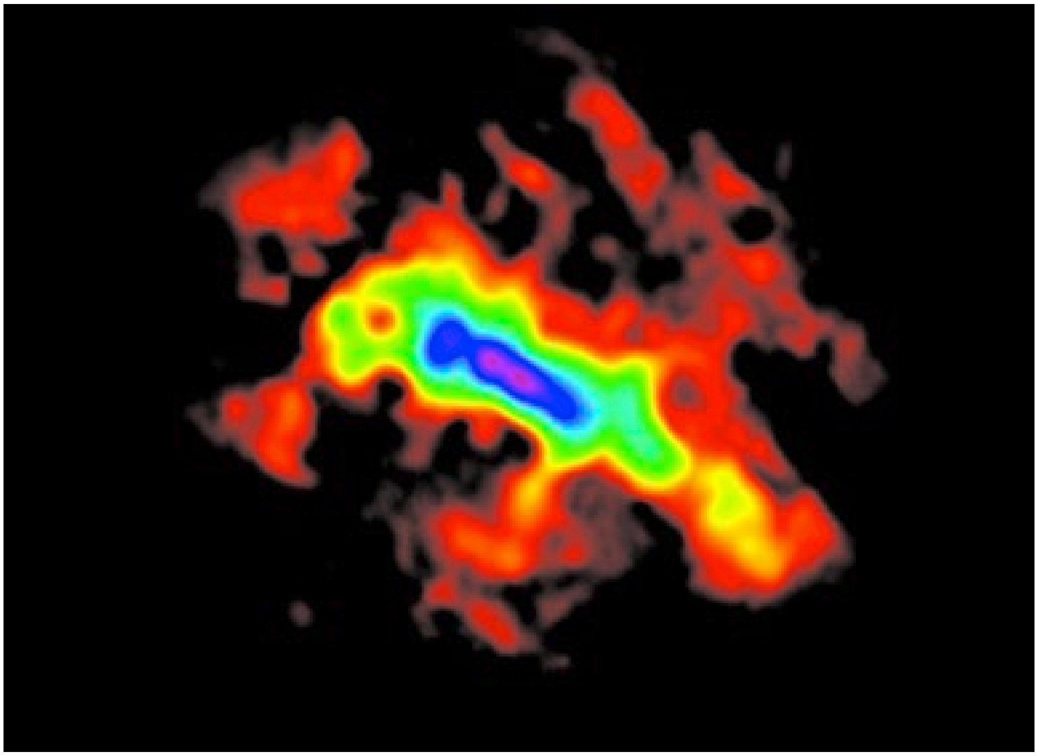


Image 7. Sculptor Galaxy.
Credit: ALMA (ESO/NAOJ/NRAO).

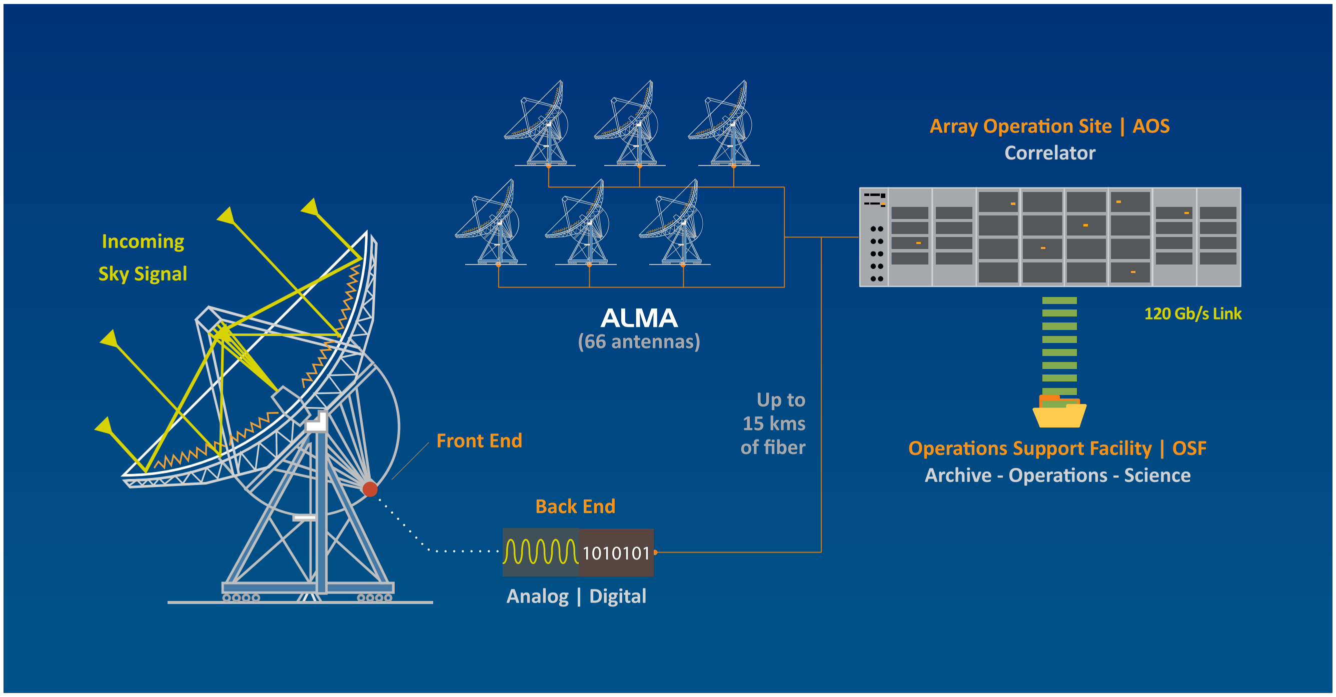
Then, after recording the radio signal from a specific point in the Universe, the radio telescope antenna moves and aims at the adjacent point, where it records the signal again. This way, it makes a sequential "sweep" of that area of the sky.

All the information about the intensities of the radio waves coming from each area of the Universe is analyzed and associated with its respective position in a unique way. With mathematic tools, astronomers can use this information to build images of the celestial object they are studying, like the Sculptor Galaxy on Image 7.

Astronomers may spend hours or even days “scanning” an object in the sky in order to obtain all of the information they need. It can then take several weeks to process the data.

At ALMA, the signals received by each antenna are combined using a technique known as interferometry, which is what makes ALMA the most powerful radio telescope today. This represents a true technical challenge, as it requires combining the signals from all antennas and electronic components to produce a high-resolution image of the object under observation, with a precision of a millionth of a millionth of an arcsecond (angular distance). In other words, ALMA is an interferometer that can function as a single, gigantic telescope equivalent to an antenna with a diameter of 16 kilometers.

Image 8.
Diagram of ALMA operations.
Credit: ALMA (ESO/NAOJ/NRAO).)



Self-assessment

1. What was Karl G. Jansky’s contribution to radio astronomy?
2. Why did a four-minute difference in the appearance of the crest of the signal lead Jansky to believe the signal came from the Milky Way?
3. What was Martin Ryle’s key idea that is the basis of interferometry?
4. What is the main difference between an optical telescope and a radio telescope?
5. In general terms, how is an image obtained by a radio telescope?
6. Why is ALMA referred to as a single observatory if it has 66 antennas?

1.5 One Telescope, Many Antennas

Each of ALMA's 66 antennas–which are either 7 or 12 meters in diameter–represents a technological and engineering design achievement. Furthermore, these antennas must be able to withstand the extreme conditions in the place where they are situated: the Chajnantor Plateau, with its strong winds, intense light and temperatures that vary from 20 to -20 degrees Celsius. Although it is one of the driest places on the planet, there can be occasional snowfall.

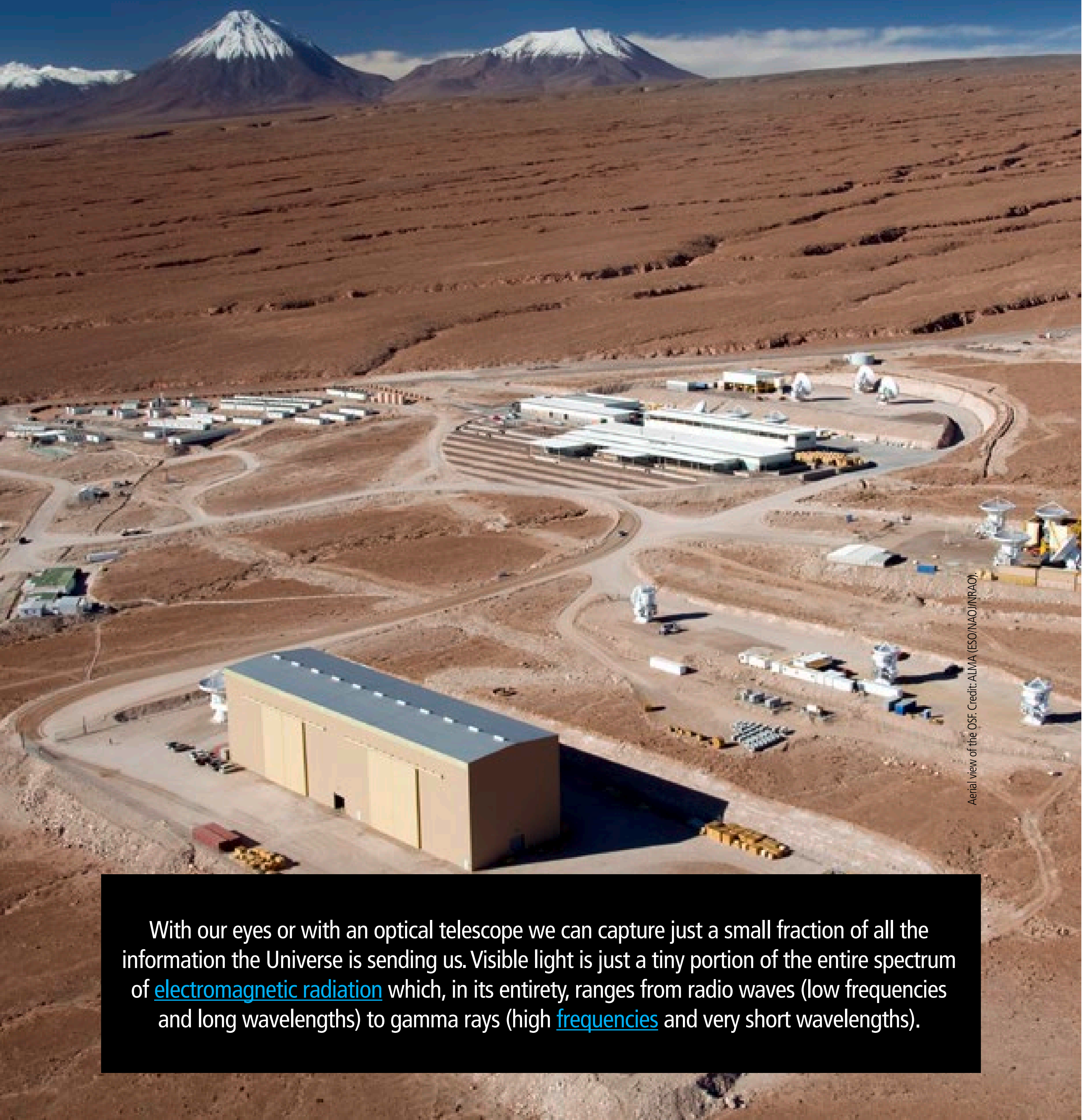
But the ALMA antennas have even more remarkable characteristics. Because the power of an interferometer depends on the location of each antenna with respect to the others, the antennas can be repositioned depending on what is being observed in the Universe. This means that unlike a telescope that is built and remains in the same place, ALMA's antennas are solid enough to be moved between concrete platforms without suffering damage to their high-precision mechanisms. This is done using two transporter trucks, Otto and Lore, designed especially for this purpose (Image 9).

Because of its many movable antennas, the total area of the ALMA interferometer is slightly more than 6,500 square meters, equivalent to a soccer field. The antennas can be distributed across the plateau with distances between them varying from 150 meters to 16 kilometers. In other words, thanks to the technique of interferometry and repositioning, ALMA has a variable and very powerful "zoom" lens for scrutinizing the Universe.

The further the antennas are situated from each other, the more details of the observed object that can be captured. Thus, ALMA can probe the Universe at millimeter and sub-millimeter wavelengths with unprecedented sensitivity and resolution, and with a view that is up to 10 times more precise than the Hubble telescope.

Image 9. Otto and Lore, the ALMA antenna transporters, in action. Credit: ALMA (ESO/NAOJ/NRAO).

2. The Physics of Radio Astronomy



Aerial view of the OSF. Credit: ALMA (ESO/NAOJ/NRAO).

With our eyes or with an optical telescope we can capture just a small fraction of all the information the Universe is sending us. Visible light is just a tiny portion of the entire spectrum of electromagnetic radiation which, in its entirety, ranges from radio waves (low frequencies and long wavelengths) to gamma rays (high frequencies and very short wavelengths).

2.1 Electromagnetic Radiation

Capturing electromagnetic waves from the Universe enables us to learn more about the objects that generate them. But why and how is an electromagnetic wave generated?

Waves are a phenomenon we experience daily: sound, light, ocean waves or throwing a rock into a peaceful lake are just some examples that allow us to observe the same pattern. In all of these examples, there is a disturbance in a given medium, such as pressure on air, a wave in the ocean, or light in a vacuum. And in all of these cases energy is transported rather than matter.

In general, waves are characterized by their length, frequency and amplitude (see Image 10). Wavelength is the distance between two consecutive crests in a wave; it is measured in meters and its derivative units (cm, mm, nm, among others). Frequency, on the other hand, is the number of times that an oscillation or cycle occurs in one minute and is measured in Hertz (Hz), where 1 Hz is equal to 1 cycle per second.

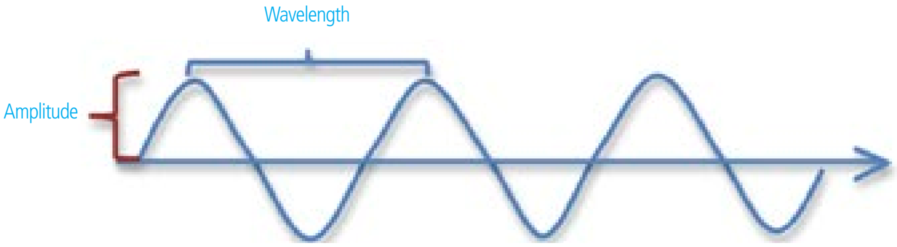


Image 10. Description of a wave showing its wavelength, where the x axis corresponds to distance.

Length and frequency are related to each other through the speed of the wave (“v”). In the case of sound waves, the speed of sound has a value of 321 m/s. Meanwhile, the speed of electromagnetic waves is referred to by the letter “c,” known as the speed of light, and it has a value of c=300,000,000 m/s.

The equation that relates these variables is:

$$c = \lambda f$$

In other words, the speed of a wave is the product of the wavelength and its frequency.

On the other hand, the amplitude of wave A corresponds to the “height” of the crest measured from the baseline and is related to the energy transported by the wave.

The sky is a constant show of fireworks that we cannot see! This invisible radiation has different properties depending on the wavelength; in a certain sense, it’s as if they had different colors. The electromagnetic spectrum is divided into different categories according to wavelength: radio, microwave, infrared, visible, ultraviolet, X-rays and gamma rays.

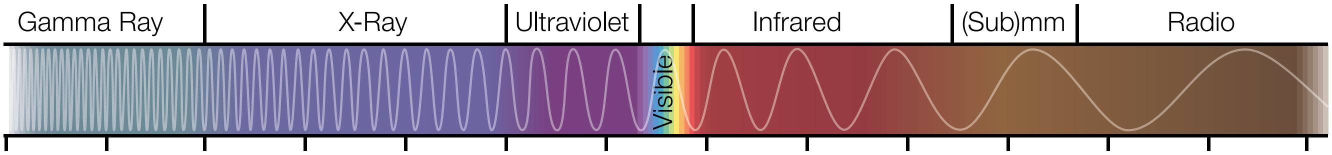


Image 11. Electromagnetic spectrum. The range of visible light is quite narrow, compared to the electromagnetic spectrum. Towards the left, radiation has more energy, and to the right, less. Credit: ALMA (ESO/NAOJ/NRAO).

By observing space with telescopes that are capable of detecting different types of light, i.e. different kind of electromagnetic radiation (see Image 11), astronomers can expand and deepen the ways in which they study the Universe. Without these telescopes, some celestial objects would remain completely invisible. For example, when a star is behind a cloud of space dust, the visible light it emits doesn't reach us, but radio waves can cross through the cloud so the star can be detected.

In addition, by observing the electromagnetic radiation of an object in different wavelengths, we can learn about the different physical processes that occur in it. Each set of observations, in varying types of radiation, contributes complementary information, as can be seen in Image 12.

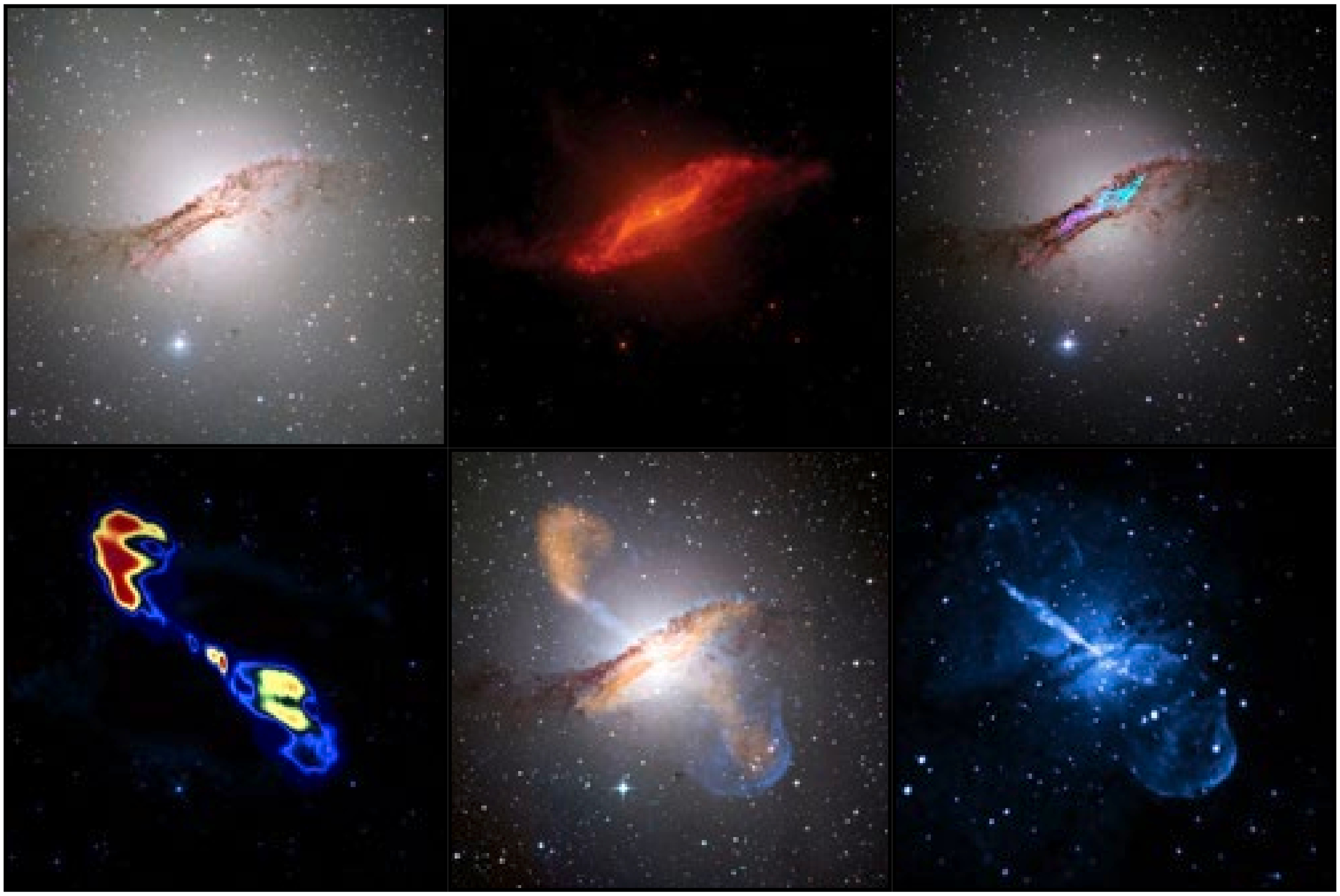


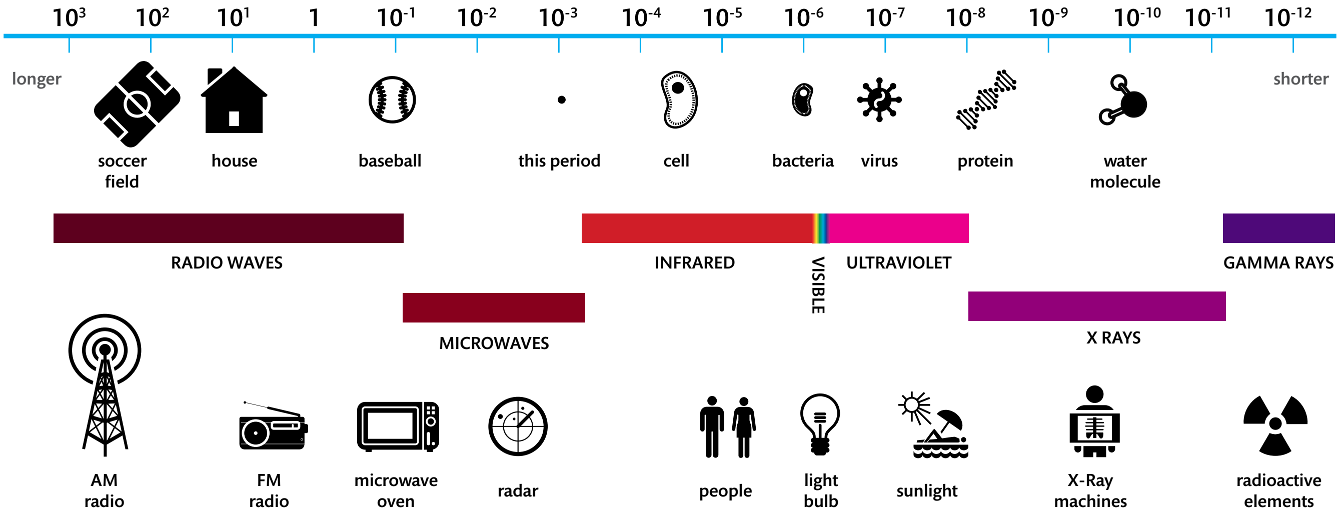
Image 12.
Six images of the same object taken with different ranges of wavelength.
Credit: ALMA (ESO/NAOJ/NRAO).

2.2 Radiation in Everyday Life

With the exception of visible light, all electromagnetic radiation is a type of invisible light that cannot be detected by the human eye. But even though we can't see it, we use this radiation every day (see Image 13): when we listen to music on the radio (radio waves), when we heat food in a microwave oven (microwave), when we change the channel on the TV with a remote control (infrared waves), when our skin is tanned by the sun (ultraviolet waves) and when we have X-rays taken at the hospital (X-ray waves).

The only radiation we don't commonly use is gamma rays, which are generated by radioactive processes and are harmful to us, due to the high level of energy they carry and their high frequency (we know that the shorter the wavelength, the greater the energy). This relationship between the energy and frequency of a photon was discovered by German physicist Max Planck, who found that energy is not emitted or absorbed continuously, but rather in "energy packets" known as quanta.

Image 13. Electromagnetic spectrum, uses and orders of magnitude.



2.3 The Origin of Electromagnetic Radiation

Electromagnetic radiation is generated by diverse physical processes, so studying it provides important information about the source. For example, cold objects in space radiate invisible light at the red end of the spectrum and emit less light than hot objects such as stars. Visible light can be generated in a variety of processes and its wavelength determines its color. Colors we can see with our eyes have wavelengths between 400 and 700 nanometers, ranging from blue light to red light. Radiation with wavelengths in this range is known as optical radiation, or more commonly normal or visible light. Electromagnetic radiation with wavelengths shorter than 400 nanometers or longer than 700 nanometers is invisible to the human eye.

The Hertzsprung’Russell diagram (Image 14) summarizes much of the knowledge we have today about stars. One of the things we can see is precisely the relationship between the temperature and color of a star: this is why the surface of the Sun, with a temperature of 5,778 Kelvin (5,505°C), shines more intensely in those wavelengths that our eyes can see or interpret as yellow-green, and which correspond to about 502 nanometers. The coldest stars look red and the hottest ones appear blue.

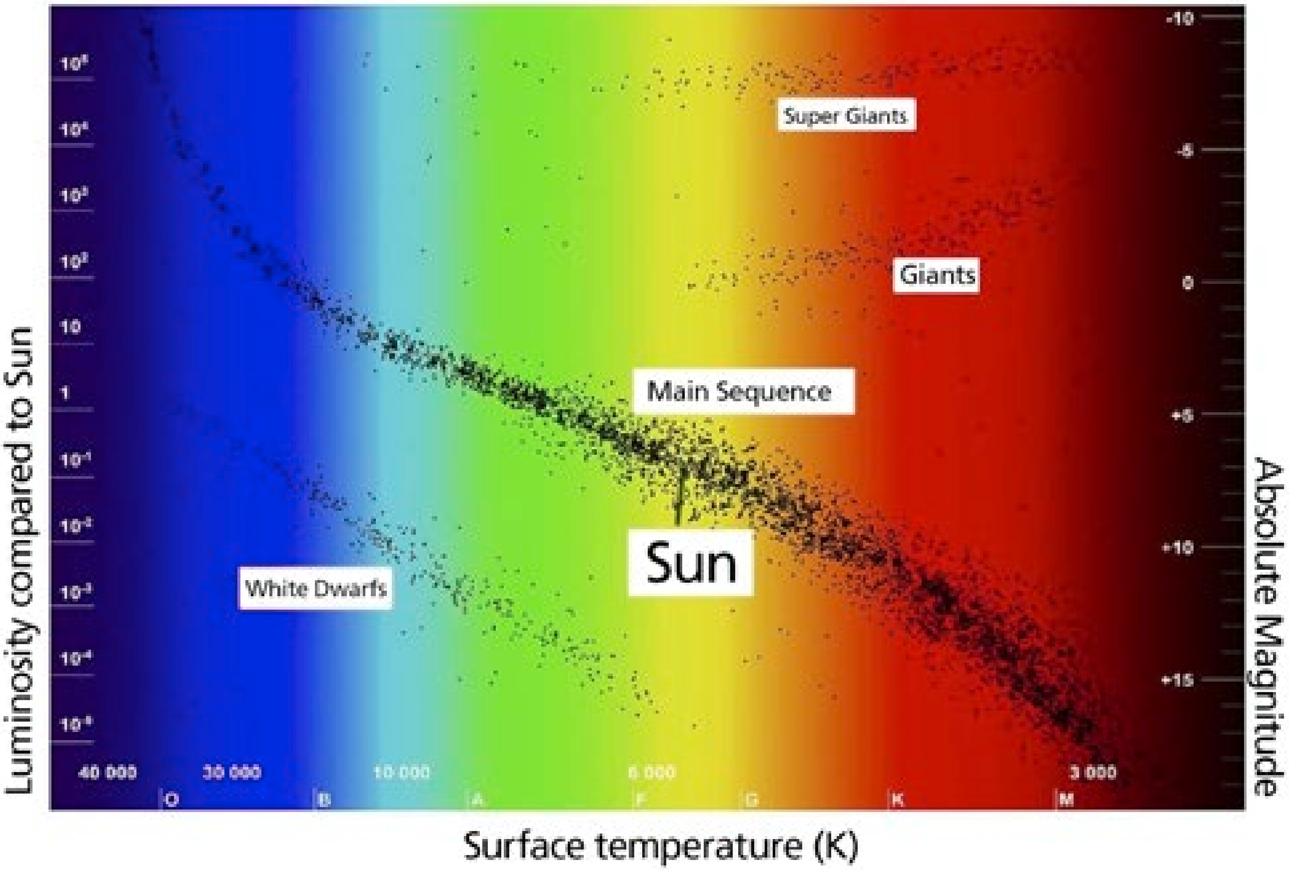


Image 14.
Hertzsprung-Russell diagram.

2.3.1 Thermal Radiation

One of the most common processes that generates electromagnetic radiation is thermal radiation, which can be easily perceived by moving your hand close to a hot object or observing a hot, incandescent iron glowing in the dark. Thermal radiation cannot be seen by the human eye, but it can be seen with an infrared camera (see Image 15).

Image 15. Two photographs of the same person taken with a normal camera (left) and an infrared camera (right). Credit: NASA/IPAC.

To explain this process, in 1862 physicist Gustav Kirchhoff introduced a theoretical object or ideal that he referred to as a black body. The black body absorbs all incident light and thermal radiation without reflecting any of this radiation or allowing it to pass through it.

Although the black body is an idealized object, an analogy is useful for imagining it: Suppose that you have a hollow metal sphere, with a highly polished inner wall. You make a tiny hole in the surface. It is easy to imagine a ray of light that enters and is reflected successively in the interior; in other words, all light that enters through the hole is reflected indefinitely in the interior without the possibility of escape (see Image 16). The black body should not be confused with a black hole, which is another theoretical object.

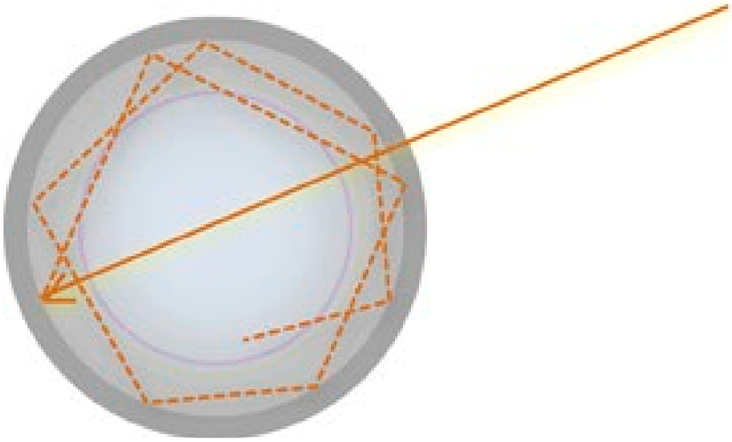


Image 16. One way to imagine a black body: The ray of light enters the sphere and is reflected indefinitely.

Although it is called a black body, that doesn't mean it is dark; on the contrary, it emits light that is known as **black body radiation**. The radiation emitted by a black body has differing wavelengths along a continuum, as can be seen in Image 17.

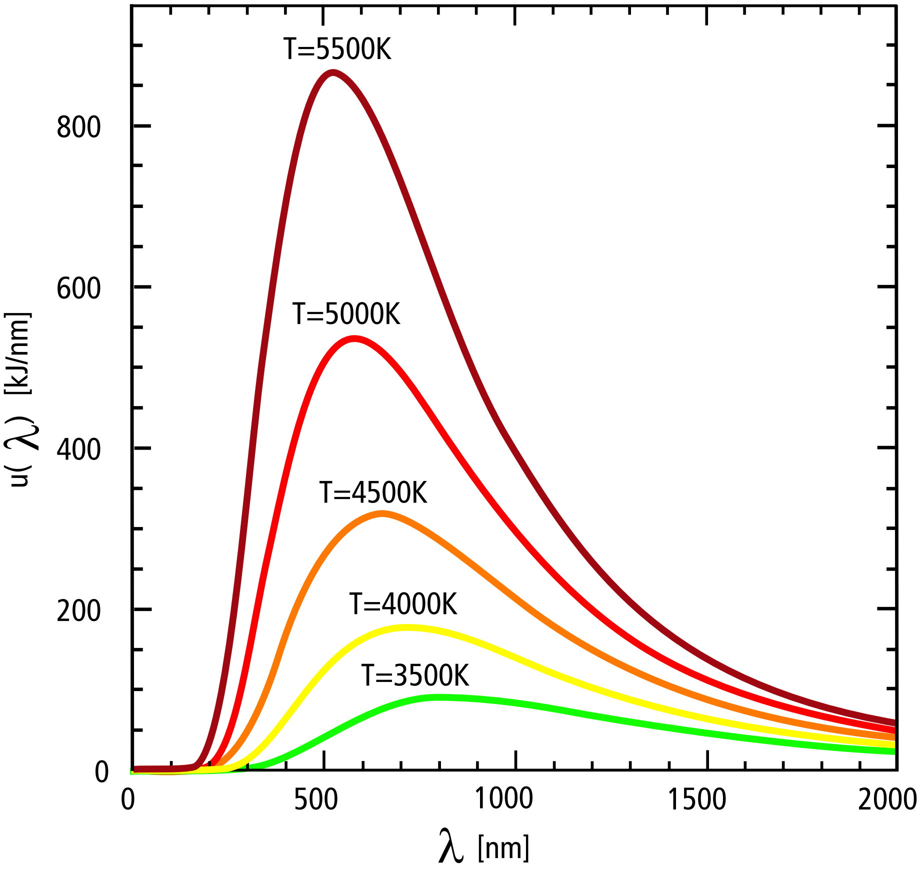


Image 17.
Graph of the radiation of a black body, showing several curves and the temperatures of the black body (3,500 K = 3,227ºC). It is also evident that there is a maximum emission, for example at 5,500 K the maximum is found at a wavelength of 500 nanometers (1 nm = 10^{-9} m). Credit: Wikipedia GPL

As the temperature of the black body increases, it absorbs energy, so the maximum emission point is displaced to smaller wavelengths on the spectrum. For example, in Image 17 you can see that at 3,500 K the maximum wavelength is almost 800 nm. If the temperature increases to 4,000 K, the wavelength at which the emission maximum occurs becomes 700 nm. If we recall that wavelength is inversely proportional to frequency (), as wavelength decreases, the frequency increases, moving from infrared to visible.

This explains why a piece of metal turns incandescent red (predominantly wavelengths around red) when it begins to heat up, and if the temperature continues climbing, it eventually becomes white (wavelengths near the middle of the visible range).

The radiation of a black body has a characteristic spectrum that depends solely on the temperature of the object. Various astronomical objects radiate with a spectrum that is similar to that of a black body, at a specific temperature.

Relationship between temperature and wavelength

The maximum emission wavelength, $\lambda m\acute{a}x$ of the distribution of a black body based on temperature T, is given by Wien's displacement law:

$$\lambda m\acute{a}x = bT$$
$$(\mathrm{b} = 2.897769 \times 10^{-3}\ \mathrm{m{\cdot}K})$$

where b is known as Wien's displacement constant.

Relationship between energy emitted and temperature

Similarly, the total energy emitted every second by a section of the object is directly proportional to the fourth power of the object's temperature. This relationship is known as the Stefan-Boltzmann law.

$$E = \sigma T^4$$

where T is the effective temperature, in other words the absolute temperature of the surface (measured in Kelvin) and sigma (σ) is the Stefan-Boltzmann constant, $\sigma = 5{,}67\mathrm{x}10^{-8}$ ($\mathrm{W/m^2\ K^4}$)

To summarize, some of the characteristics of thermal radiation are:

- Hotter objects emit light with shorter wavelengths and higher frequencies.
- The hottest objects emit the brightest light.

Thus, the light that comes from vast cold clouds in interstellar space at temperatures of just a few dozen degrees Kelvin above absolute zero, as well as from some of the earliest and furthest galaxies in our Universe, will have millimeter and sub-millimeter wavelengths, situating them between infrared light and radio waves on the electromagnetic spectrum, precisely where ALMA is observing.

Astronomers can use this radiation to study the chemical and physical conditions in molecular clouds, which are dense regions of gas and dust where new stars are beginning to form. These regions of the Universe are often hidden from visible light, but they shine intensely in the millimeter and sub-millimeter part of the spectrum.

2.3.2 Non-thermal Radiation

There are other mechanisms, not associated with an object's temperature, that generate radiation. These are briefly presented for reference purposes.

Much of the radiation in our galaxy and particularly the radiation discovered by Jansky is generated mainly by the interaction of charged particles with magnetic fields.

When a charged particle traveling at a certain speed enters a magnetic field, a force is exerted on it that deviates it in a circumferential trajectory. This is known as Lorentz force. Because the particle is accelerated, it emits light, which under non-relativistic conditions–that is, its speed is much lower than the speed of light–is known as cyclotron radiation But when its speed is close to the speed of light, it emits much stronger radiation, known as synchrotron radiation. An example of this are quasars, which emit synchrotron radiation in addition to visible light and X-rays.

An important difference between these mechanisms is that while the intensity of thermal radiation increases with frequency, the intensity of non-thermal radiation usually decreases with frequency.

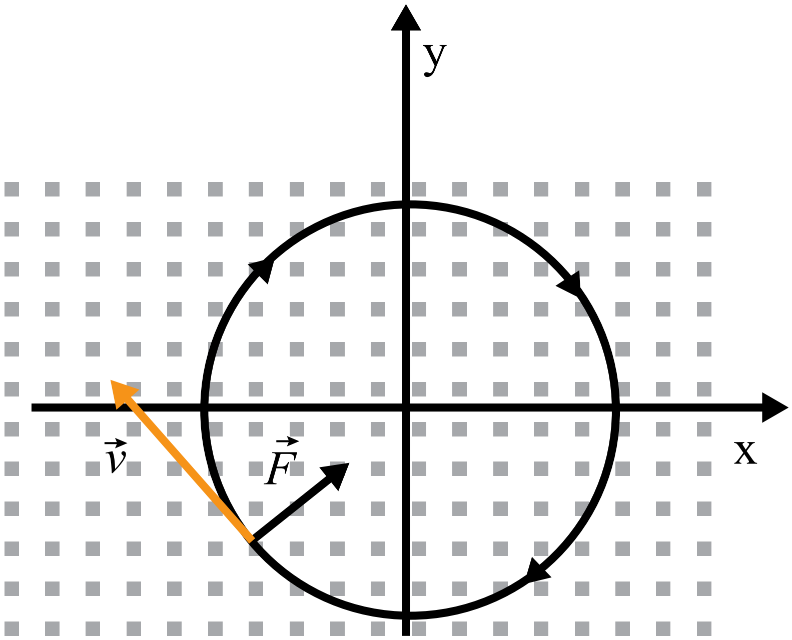


Image 18. Charged particle in a magnetic field that exits the plane of the paper. The magnetic field generates a force that is always perpendicular to the plane formed by the velocity vector and the magnetic field vector. Credit: Pablo Torres.

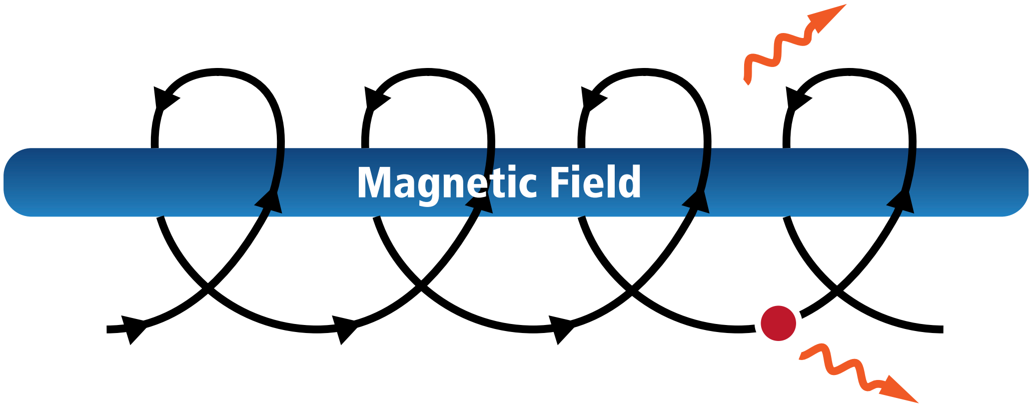


Image 19. A particle that moves in the magnetic field; its acceleration generates cyclotron radiation. Credit: NRAO.

2.4 How Waves Travel Through Space

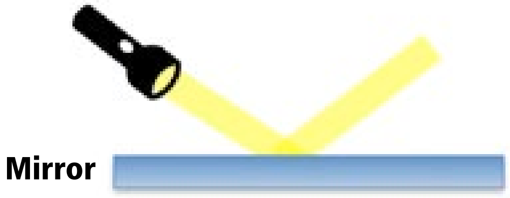
When electromagnetic waves are emitted, they travel through space in a straight line. On their path they may encounter different chemical substances, such as those found in clouds of dust or gas. They interact with these in different ways: they may be absorbed, reflected, or pass directly through them without undergoing any major changes.

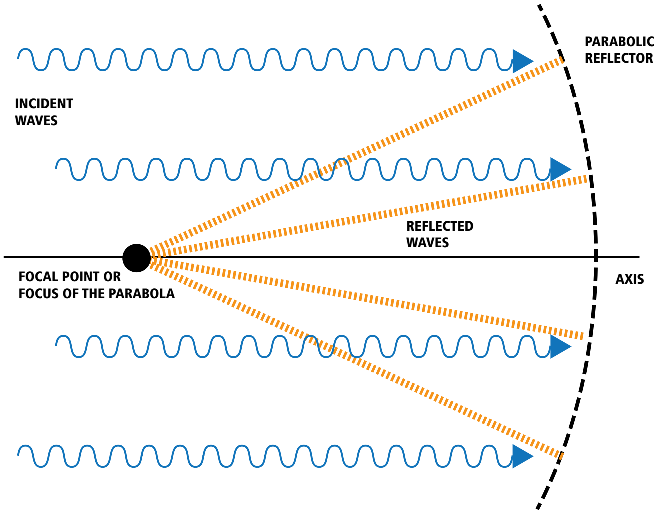
When a wave encounters a change of medium, the following phenomena may be observed:

2.4.1 Reflection

Reflection occurs when waves change direction after colliding with a surface (see Image 20). This phenomenon is observed clearly in a mirror, where light waves change the direction of their movement. A similar phenomenon is used in reflecting telescopes, where a mirror with a parabolic shape deviates the incident light, parallel to the optic axis, toward a single point, known as the focus. Radio telescope antennas concentrate incident electromagnetic waves on the receiver.

Image 20

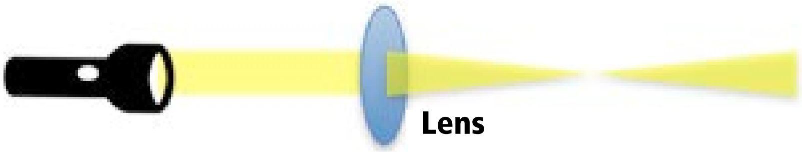




2.4.2 Refraction

Refraction happens when waves cross or pass through a material medium to another and experience a change in direction and speed of propagation. The variation in these parameters will depend on the refraction index of the material media involved. This phenomenon is observed when light crosses water or when it passes through a glass lens (see Image 21).

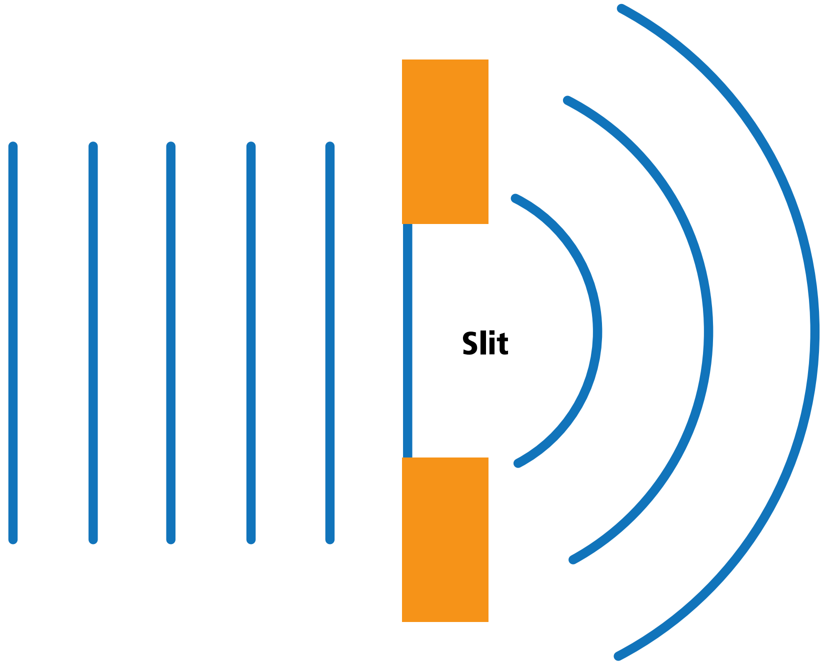
Image 21



2.4.3 Diffraction

Diffraction is a phenomenon characteristic of waves that occurs when a wave is deviated by an obstacle or by passing through a slit (see Image 22). We experience this every day when we hear sounds coming from adjacent rooms. It can also be observed in the case of a radio source that is hidden by the Moon, through oscillations in its brightness rather than an abrupt disappearance.

Image 22



Diffraction depends on the relationship between the wavelength and the size of the object. This is why it doesn't seem to be observable in visible light, as the wavelength is very small. Observing this phenomenon requires a slit that is the same size as the wavelength; for example, for green light, a 5,500-nanometer slit would be required. This is what happens in reflective telescopes, where diffraction on the arms supporting the secondary mirror can alter images of stars.

Deviations of electromagnetic waves caused by diffraction when colliding with a mirror, the dish of an antenna or a lens create a fundamental limit in the fine details that can be detected by the telescope, which is known as resolution power.

In the case of a telescope, either optical or radio, resolution depends on the diameter of its primary mirror or the dish, respectively, and on the length of the wave that is being observed. For example, if the dish of an antenna has a diameter D measured in meters, and operates on a wavelength λ, also measured in meters, then its maximum resolution expressed as the angle θ (expressed in radians) is approximately:

$$\theta \approx \lambda / D$$

In the equation above, the angle θ is measured in radians rather than degrees. There are 2π radians in a circumference, as opposed to the typical 360 degrees. Therefore, to convert radians to degrees, you must multiply by $360/2\pi$. As observed in the expression, the radian is not a unit of measure like a meter or a second.

Astronomers often measure angles smaller than a degree, in both arcminutes and arcseconds. The terms "minutes of arc" or "seconds of arc" are also used. There are 60 arcminutes in a degree, and 60 arcseconds in an arcminute (and therefore 3,600 arcseconds in a degree).

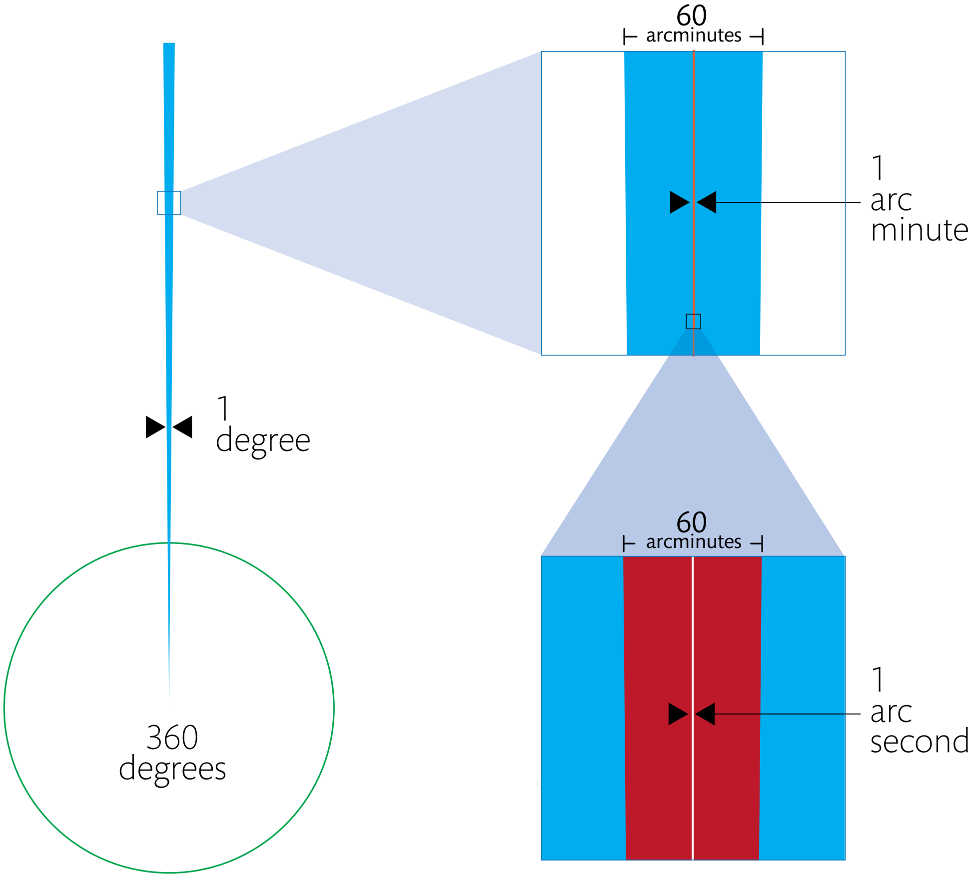


Image 23. Relationship between angle, arcminute and arcsecond. Credit: ALMA (ESO/NAOJ/NRAO), A. Peredo.

When we refer to relatively large distances with respect to the size of the object observed, we can use a simple ratio to convert from angles to distances. Thus, the sides of a defined angle can be considered equal to the distance to the object and much greater than the subtended angle (x), so we can apply the approximation for small angles, which is:

$$x \approx r\,\theta$$

where θ is the angle (expressed in radians) that subtends the arc of length x at a distance r.

2.4.4 Resolution at ALMA Wavelengths

Let's apply these results to ALMA, which observes the Universe at wavelengths around 1 mm, in comparison to visible light, which has wavelengths of about 500 nm:

$$\theta \approx \lambda/D$$

For the radio telescope:

$$\theta \approx 1x10^{-3} \text{ m} / 12 \text{ m} \approx 10^{-4} \text{ rad} \approx 0{,}057\ ^{o}$$

For an optical telescope of the same size:

$$\theta \approx 5x10^{-9} \text{ m} / 12 \text{ m} \approx 10^{-10} \text{ rad} \approx 2{,}4x10^{-7}\ ^{o}$$

The results show that resolution power is lower for radio waves than in the visible spectrum. This is why millimeter and sub-millimeter telescopes such as ALMA have to be even larger than visible light telescopes to be able to capture these wavelengths. It is also necessary to use the interference technique.

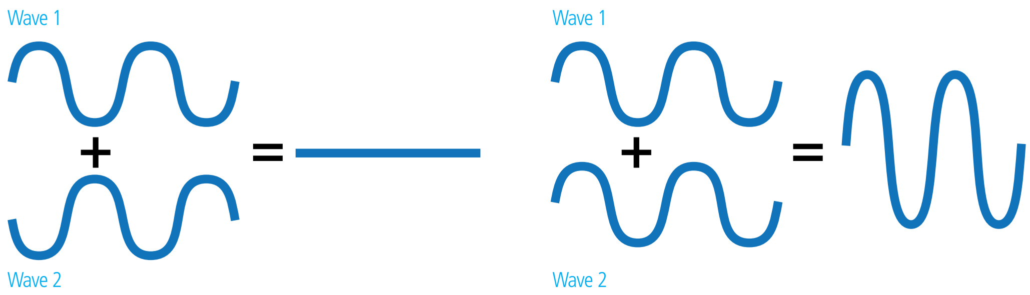
2.4.5 Interference

Interference refers to the capture of an unwanted radio signal, such as when a radio telescope captures a radio signal generated by human activity, rather than signals coming from natural sources.

A second meaning, applied to a phenomenon of waves themselves, consists of combining two or more waves at the same point in space, resulting in greater intensity (constructive interference) or reduced intensity (destructive interference). For this to occur, the waves must be lined up, that is, their crests and valleys must be in phase. Destructive interference occurs when at a certain point in space a valley is superimposed on a crest, while constructive interference occurs when the crests or valleys coincide.

This same principle is used in the technique known as interferometry, where multiple individual telescopes can be linked together and their signals combined to simulate the effect of a single, gigantic telescope.

Image 24. Destructive and constructive interference. In the image on the left, the crest of wave 1 coincides with the valley of wave 2. In the image on the right, the crest of wave 1 coincides with the crest of wave 2. Credit: astro-canada.ca.



The resolution of an interferometer doesn’t depend on the diameter of the individual reflectors but on the maximum separation between the antennas, or baselines, such that moving them further away from each other increases the resolution. The antenna signals are combined and processed by a supercomputer–the ALMA Correlator–to simulate the work of single telescope. In other words, an interferometer functions like a telescope the size of the entire array of antennas.

Increasing the distance between the antennas raises the power of the resolution of the interferometer, capturing more subtle details. The possibility of combining antenna signals separated by baselines of several kilometers is crucial for obtaining extremely fine resolution and very detailed images.

The main ALMA array has 50 antennas with a diameter of 12 meters, arranged in specific configurations with separations that vary from 150 meters to 16 kilometers between the most distant antennas. Thus, the array simulates a giant telescope, one that is much larger than any single reflective telescope that could be built.

Four other antennas with diameters of 12 meters and 12 antennas with a diameter of 7 meters make up the Atacama Compact Array (ACA), also known as the Morita Array. The 7-meter diameter antennas can be concentrated in a smaller area without interfering with each other. Due to the way in which interferometers operate, this arrangement enables them to obtain a more general image of astronomical objects that are observed, much like the wide angle lens of a photographic camera. On the other hand, the ACA’s four antennas with diameters of 12 meters can be used separately to measure the absolute brightness of objects observed, a level that can’t be measured by an interferometer.

Thus, the different radio telescope configurations allow astronomers to study the general structure of an astronomical source as well as its tiniest details. However, the antennas have to be moved when changing from a compact to a more dispersed configuration. To do this, ALMA uses transporters made specifically for this purpose. The transporters can lift the antennas (which weigh more than 100 tons each), move them several kilometers away in the high mountain plains of the Atacama Desert and then set them down on concrete platforms with millimetric precision.

2.4.6 Transparency and Opacity

The light emitted by stars or other objects in space must cross several zones before reaching Earth. Its capacity to move through regions with differing degrees of transparency depends on its wavelength. That means that while visible light can be blocked by a cloud or dust, other types of radiation can pass through them without losing energy.

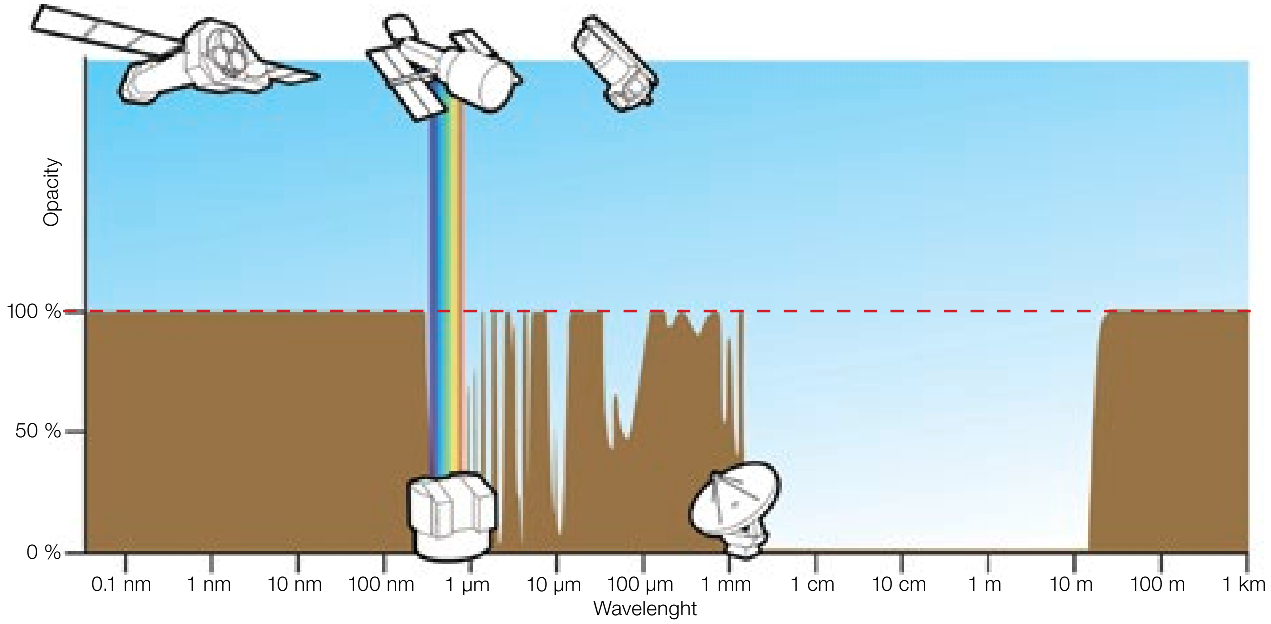


Image 25.
Atmospheric opacity. Opacity is on the vertical axis and wavelength is on the horizontal axis. The top horizontal line corresponds to 100% opacity. For visible light, which is marked by the telescope, it is transparent the same as with radio waves.
Credit: ESA/Hubble (F. Granato).

The same thing occurs when light reaches the Earth's atmosphere; this is defined as atmospheric transparency or opacity. An opacity of 100% corresponds to 0% transparency and vice versa. Image 25 shows how the atmosphere's opacity varies with respect to wavelength. At an opacity of 100%, radiation is completely blocked, while at an opacity of 0%, radiation is fully transmitted (what astronomers call the "window of observation").

The atmosphere doesn't just absorb the weak signals from space that astronomers attempt to capture using ALMA; it also emits radiation itself. The main factor that defines transparency, in the case of wavelengths observed by ALMA, is water vapor. That's why it so important that ALMA is located in a dry place at high altitude. And that is also why, after analyzing several different sites around the world, the consortium that built ALMA chose the Chajnantor Plateau, at an altitude of 5,000 meters above sea level facing the Atacama Desert in northern Chile. It is precisely that: a very dry site at a very high altitude.

The amount of water vapor is usually measured in millimeters of "precipitable water vapor" (PWV), which is the depth of the pond that would form in a place if all the water were precipitated as rain. The average PWV value on our planet is close to 2.5 cm, but extremely dry conditions are needed for sub-millimeter astronomy. On the Chajnantor Plateau, from April to December the average precipitable water vapor is approximately 1 mm, and it can even fall below 0.5 mm under certain conditions. Image 26 shows how the opacity varies with wavelength and the presence of water vapor in the atmosphere.

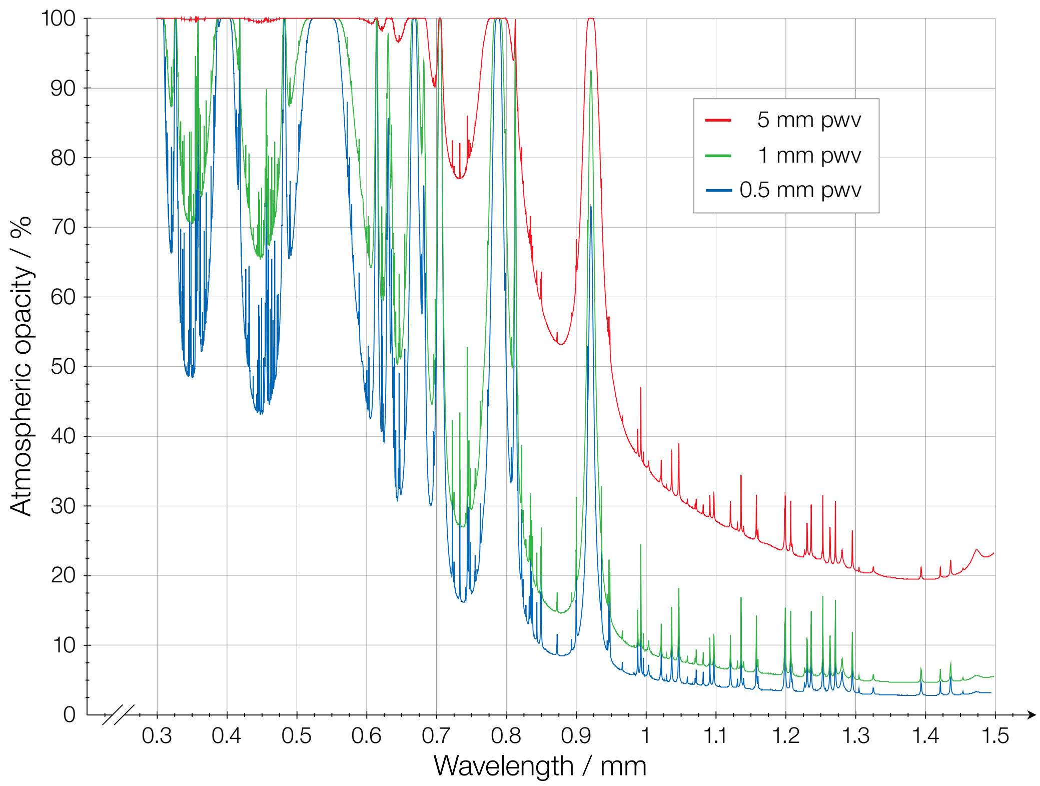


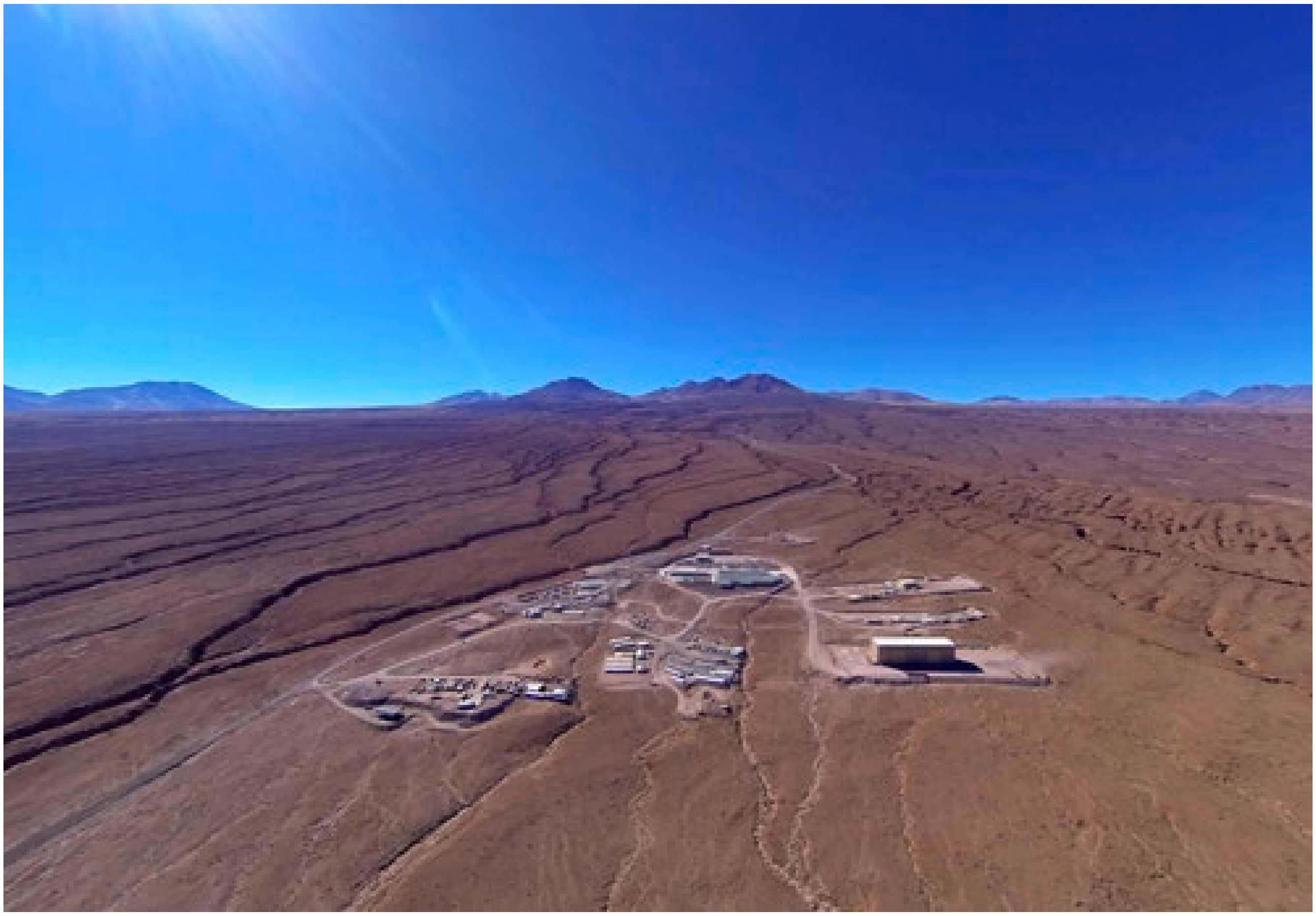
Image 26. Diagram of atmospheric opacity according to wavelength, where lines of different colors represent different levels of precipitable water vapor.
Credit: ESO/APEX

2.5 Working at High Altitudes

The site where the ALMA antennas are located is known as the Array Operations Site (AOS). At an altitude of 5,000 meters above sea level, the conditions at the site are excellent for sub-millimeter astronomy but fairly harsh for living and working. Because of this, daily operations are conducted at the Operations Support Facility (OSF), at an altitude of 2,900 meters.

At very high altitudes, atmospheric pressure is lower than at sea level, as is the amount of oxygen available. In the exercise below, we will look at how the atmospheric pressure at the ALMA site compares to sea level and other high-altitude places.

Image 27.
ALMA Operations Support Facility.
Credit: Ariel Marinkovic / X-Cam.



2.5.1 Atmospheric pressure at high altitudes: The isothermal atmosphere

We can use a simple model to study the way in which pressure decreases with altitude, assuming that pressure decreases exponentially as altitude increases. This model is called "isothermal" since we assume that the air temperature remains constant. This is not totally exact, but it is a reasonable approximation. In other words,

$$ph=p_0e-(hH)$$

where p is pressure as a function of altitude h above sea level. There are two constants in the equation: p_0 is the pressure at sea level (in other words, h = 0 meters) and H is the altitude where the pressure has fallen by a factor of 1/e; this is known as the scale height.

Imagen 28.
ALMA Operations Support Facility.
Credit: ALMA (ESO/NAOJ/NRAO)/
Erik Rosolowsky.

Self-assessment

1. For an electromagnetic wave, what is the relationship between frequency and wavelength?
2. In terms of wavelength, what are the categories of the electromagnetic spectrum?
3. What are the main characteristics of thermal radiation?
4. What is the difference between cyclotron and synchrotron radiation?
5. How is the resolution of an interferometer determined?
6. What is the main factor influencing the opacity of the Earth's atmosphere in the range of millimeter/sub-millimeter wavelengths?
7. What are the risks of working at the ALMA Array Operations Site (AOS)?

3. Exploring Our Cosmic Origins

ALMA antennas. Credit: ALMA (ESO/NAOJ/NRAO).

ALMA is the most powerful telescope for observing the cold Universe, including both molecular gas and dust and traces of radiation from the Big Bang. ALMA studies the basic components of stars, planetary systems, galaxies and life itself. By providing scientists with detailed images of stars and planets being born in gas clouds close to our Solar System, and detecting distant galaxies forming on the limits of the observable Universe, just as they did 10 billion years ago, ALMA enables astronomers to answer some of the most profound questions about our cosmic origins

3.1 The Big Bang

As the light from the Big Bang faded, the early Universe became increasingly dark. There were no stars, just gases–largely hydrogen, some helium and traces of lithium and beryllium–from which the first stars would eventually form. No one knows exactly how long this Dark Age lasted, but at some point in the first hundreds of millions of years, some stars condensed from that gas and began to shine.

The theory is that these first stars had a much greater mass and were brighter than the ones we see today. They lived for just 1 million years before exploding spectacularly, shooting into space the chemical elements accumulated deep within them.

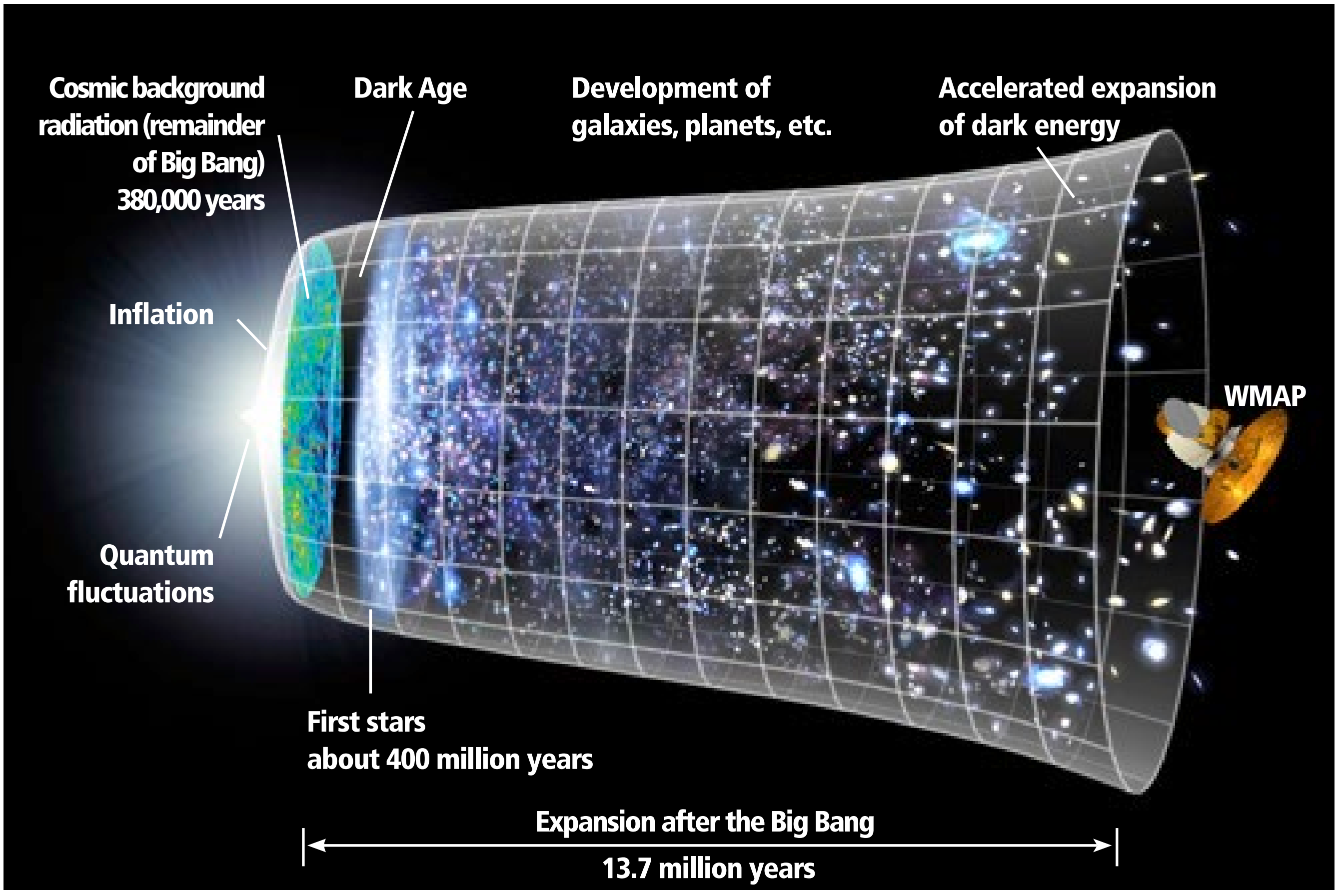


Image 29. Expansion of the Universe since the Big Bang.
Credit: NASA-WMAP.

Even today's most powerful telescopes can't detect light coming from that first generation of individual stars. The space observatories of the future will be technically capable of recording the greatest amount of light emitted by that type of star when it explodes, but there are scarce opportunities to do something like that–even once–in the lifetime of an observatory.

Paradoxically, our best hope of detecting the era of the first stars lies in one of the weakest elements in the Universe. Among the material expelled into space by those stars was the dust formed by the thermonuclear fusion of the lightest elements they contained. Thus, the first appearance of dust would become our best evidence about the life and death of the first stars.

ALMA is designed to detect dust in the early Universe. By scrutinizing deep space–remember that the further away we see, the further back we travel in time–ALMA detects the brightness of warm dust present in the most distant and therefore oldest galaxies. This is much more than can be captured in observations in visible or infrared light.

3.2 The Chemistry of the Universe

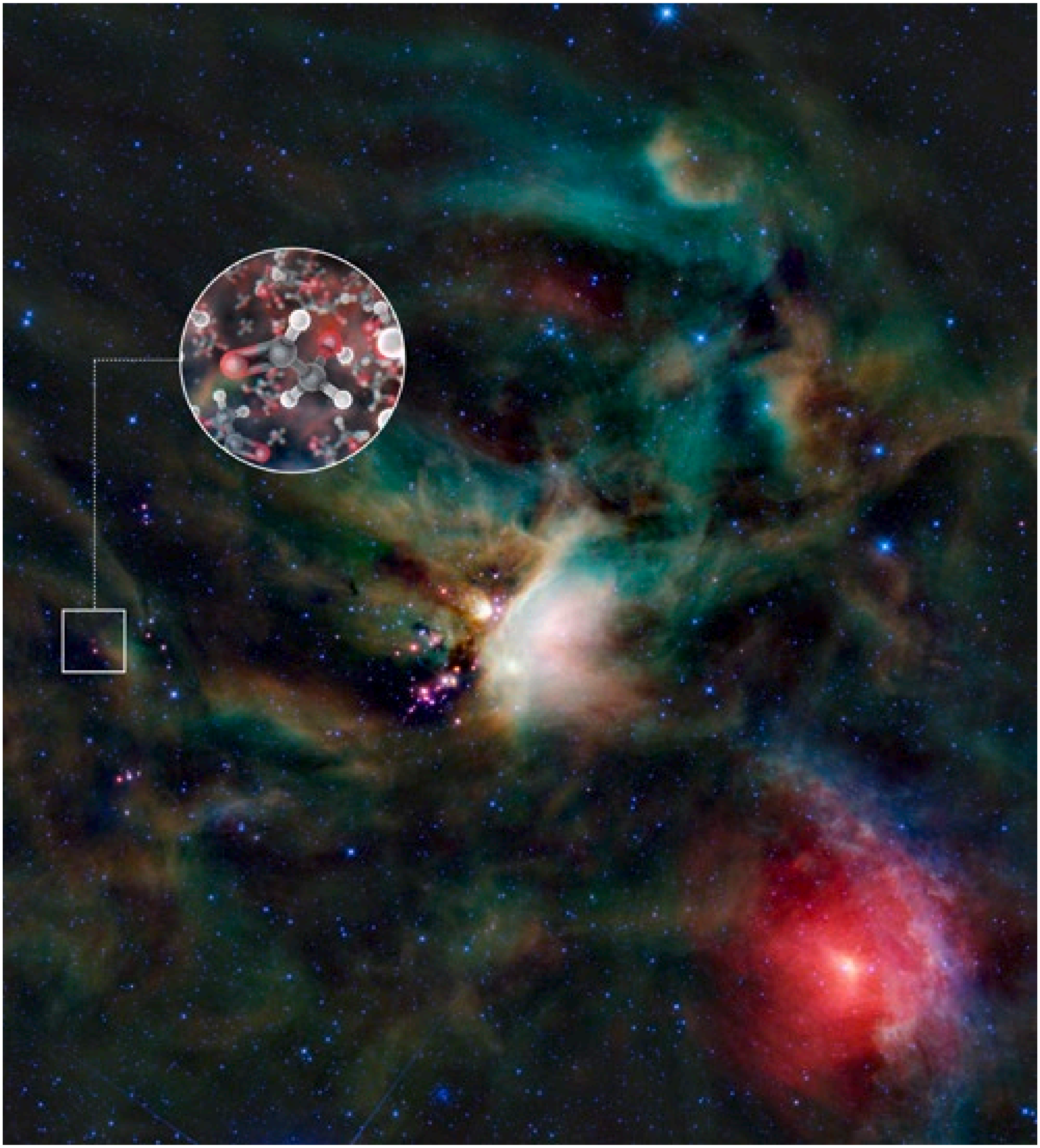


Image 30.
Glycoaldehyde molecules surrounding the IRAS 16293-2422 star.
Credit: ALMA (ESO/NAOJ/NRAO).

At a microscopic level, space landscapes reveal chemical factories of incredible complexity. Chemical elements combine to form molecules, a continuous process that diversifies, since as the molecules heat up they release dust, becoming gaseous molecules in space as can be seen in Image 30. These molecules constitute the fundamental pillars of life and feed the young planets.

If chemical elements were letters in the alphabet, the molecules would be words. Molecules are more diverse, complex and interesting than elements, but they don't survive well at the high temperatures (thousands of degrees) to which visible light telescopes are tuned. That's why the radio telescope technology such as that used at ALMA is necessary.

ALMA has an unprecedented ability to discover and measure the presence of molecules and their distribution in space. This is supporting major progress in understanding the chemistry of space–which can't be reproduced in laboratories on Earth–and the changing conditions that affect it. For example, astronomers using ALMA have already detected sugar molecules in gas surrounding a young star similar to the Sun (Image 30). This is the first time sugar has been found in space around a star like that. The finding demonstrates that the basic components of life are found at the right place and time for becoming part of the planets that form near the star.

Another example is the observation of carbon monoxide molecules, which have revealed a totally unexpected spiral structure in the material that surrounds the ancient star R Sculptoris (Image 31). This is the first time that such a structure such has been found and it was probably produced by a hidden companion star that orbits around the main star.

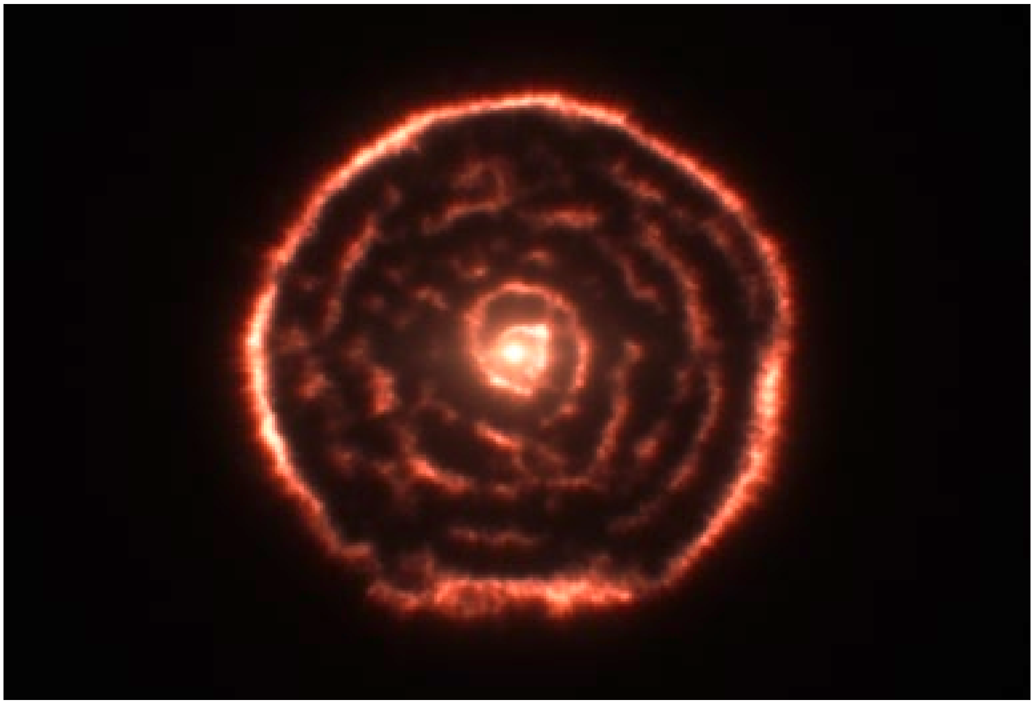


Image 31.
Spiral structure around the R Sculptoris star.
Credit: ALMA (ESO/NAOJ/NRAO)/ M. Maercker et al.

3.3 Formation of Stars and Planets

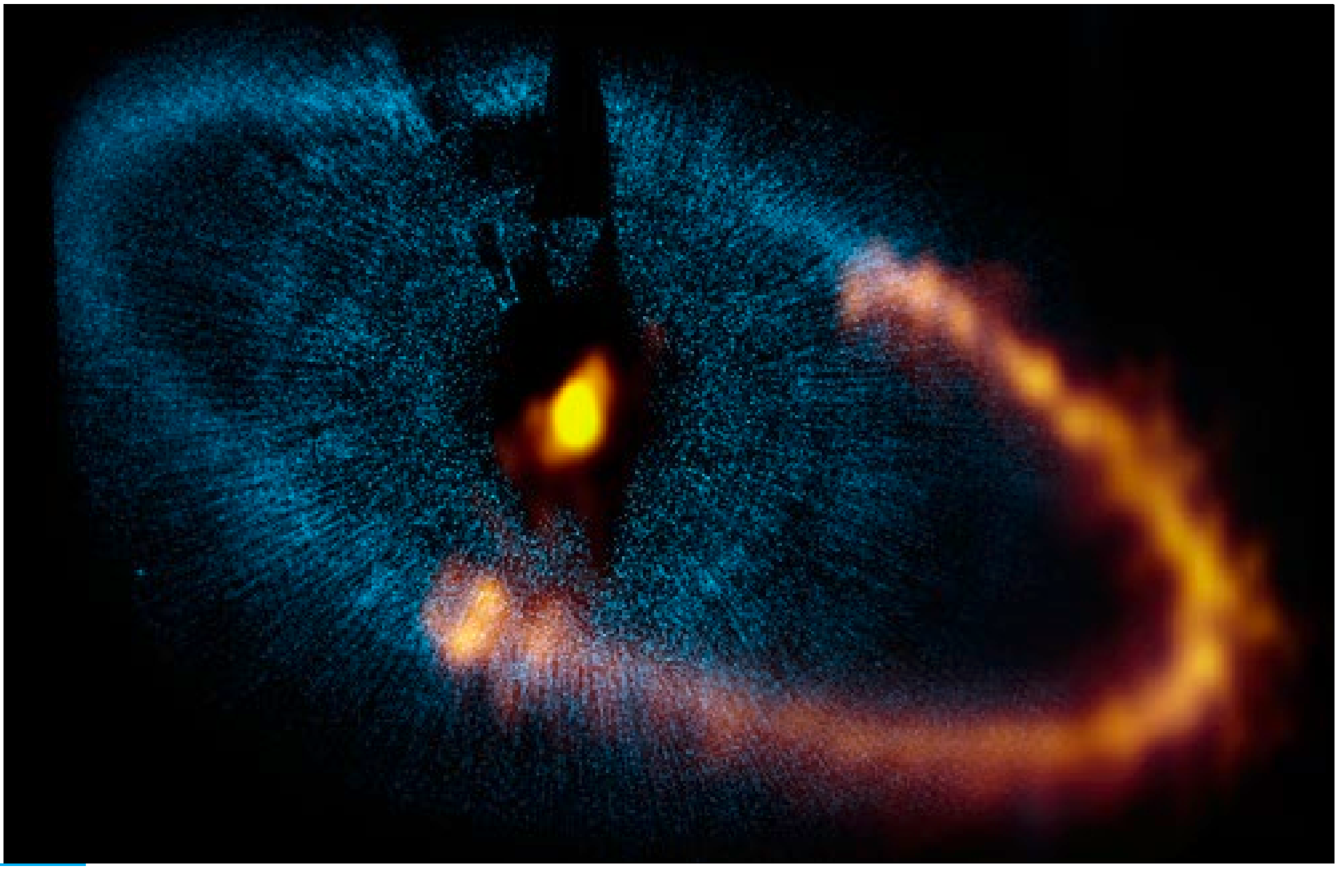
Stars shine for millions or billions of years, but their formation–which takes a few thousand years–continues to be a mystery. This is because visible light telescopes cannot see inside the dusty concentrations of gas from which stars are born. And infrared telescopes, which can show us newly born stars before they emerge completely from their dusty cocoons, can's see the development process of a star's pre-ignition.

We know that huge clouds collapse under the force of gravity to form stars. But how do they fragment into smaller clouds to become a mixture of large and small stars? How does gravity overcome the turbulence, flows and magnetic forces that resist the collapse of the cloud? Furthermore, how do stars–destined to become massive–continue to accumulate gas once they have been ignited? How come the wind that flows from these stars doesn't stop their expansion?

ALMA will help untangle these mysteries by observing star formation clouds in depth, detecting the gentle light emitted by matter that is just beginning to heat up and even mapping the movement of that matter.

According to what we now know, planets form around a new star by condensing into a disk of molecular gas and dust embedded in a larger molecular cloud. The condensation increases and forms giant planets that heat up, sweeping their orbits on the disk and even bending it. The gas that remains in the disk finally disappears, leaving behind planets and a disk of dust and debris.

Image 32. Combined view of the dust ring around the Formalhaut star captured by the Hubble space telescope (blue) and ALMA (orange). Credit: ALMA(ESO/NAOJ/NRAO) and Hubble space telescope, NASA/ESA.



ALMA studies all the phases of planet formation. It probes protoplanetary disks–planet embryos–in high resolution; it can capture the increase in brightness and temperature of planets in formation and it directly detects how giant planets clean their orbits on the disks. ALMA can find more planets by measuring the incredibly small effects they have on stars that orbit and this may help us measure the mass of some planets that have already been discovered. Also, ALMA can examine disks of dust and debris that remain around the stars once the gas has disappeared. Using the ALMA telescope, a group of astronomers discovered that the planets orbiting the Fomalhaut star must be much smaller than originally believed (Image 32).

3.4 Studying the Sun

Wisely, most telescopes are never pointed at the Sun. However, ALMA can easily study our star because the surface of its antennas dissipates the heat, focusing the millimetric waves of the light spectrum without burning the antennas or receivers.

ALMA investigates the huge eruptions on the Sun and their emission of particulates at a high speed. It studies the structure and evolution of solar prominences and filaments, which are gas threads with a temperature of 6,000°C suspended in the solar atmosphere (corona) at 3,000,000°C.

Even today, it remains a mystery why the Sun's atmosphere is so hot. ALMA probes the Sun's atmosphere just below the point where the temperature drastically increases, helping us understand areas of the solar atmosphere that are impossible to study any other way.

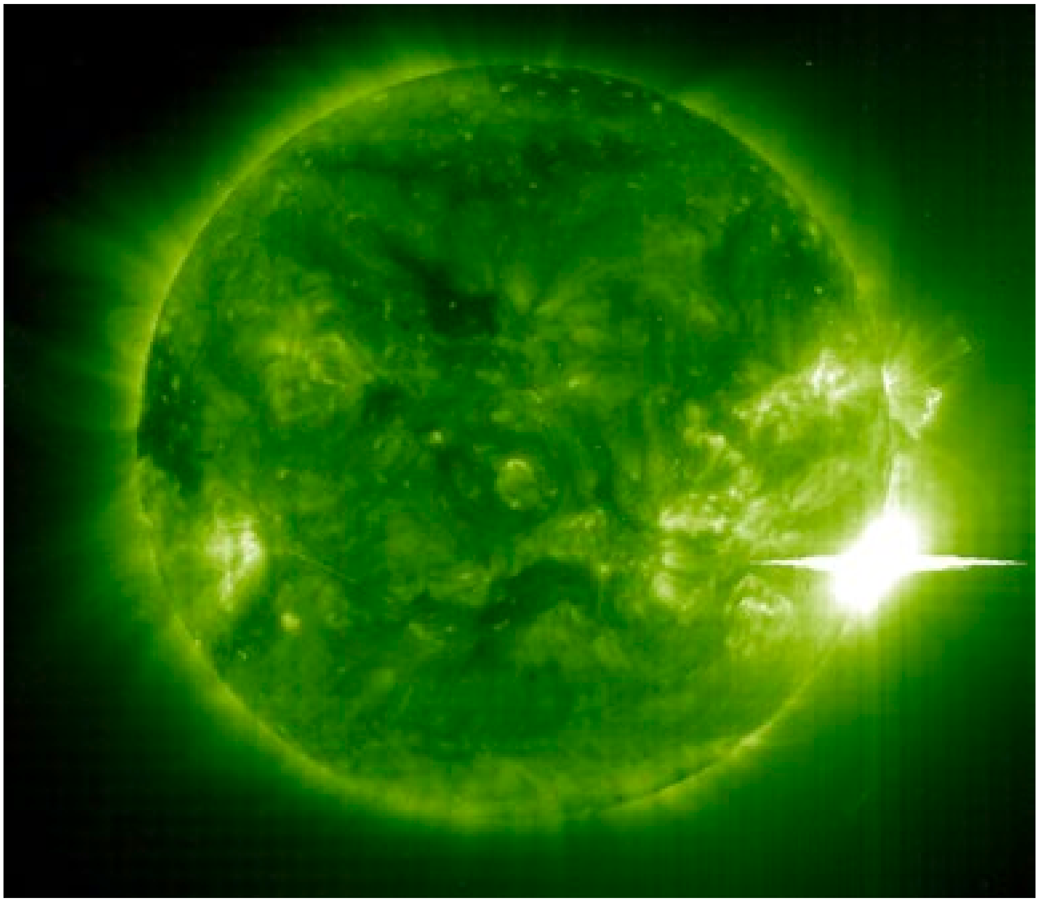


Image 33. Possibly one of the most intense solar eruptions ever seen, in 2003, as viewed by the SOHO satellite. Credit: ESA/NASA.

3.5 The Sun and its Environment

The Solar System constitutes the small part of the Universe that we can visit with robotic probes. But because of their high cost only a few probes can be launched, and there are thousands of planets, asteroids and comets to explore. Therefore, much of the observation has to be done from Earth.

ALMA observes planets and measures their winds. It analyzes the molecules emitted by comets and asteroids, even when they are at their most active as they pass by the Sun, a time when other telescopes can't observe them.

Image 34. C/2001 Q4 comet,
Credit: T.A. Rector

Studying the composition of comets provides us with a new perspective on the early formation of the Solar System, as does observation of molecules scattered in space.

ALMA will discover thousands of new objects in the Kuiper Belt (where Pluto is located), observing the light they emit rather than the Sun's light reflecting off them–which is what has been studied until now–and enabling us to calculate their real sizes.

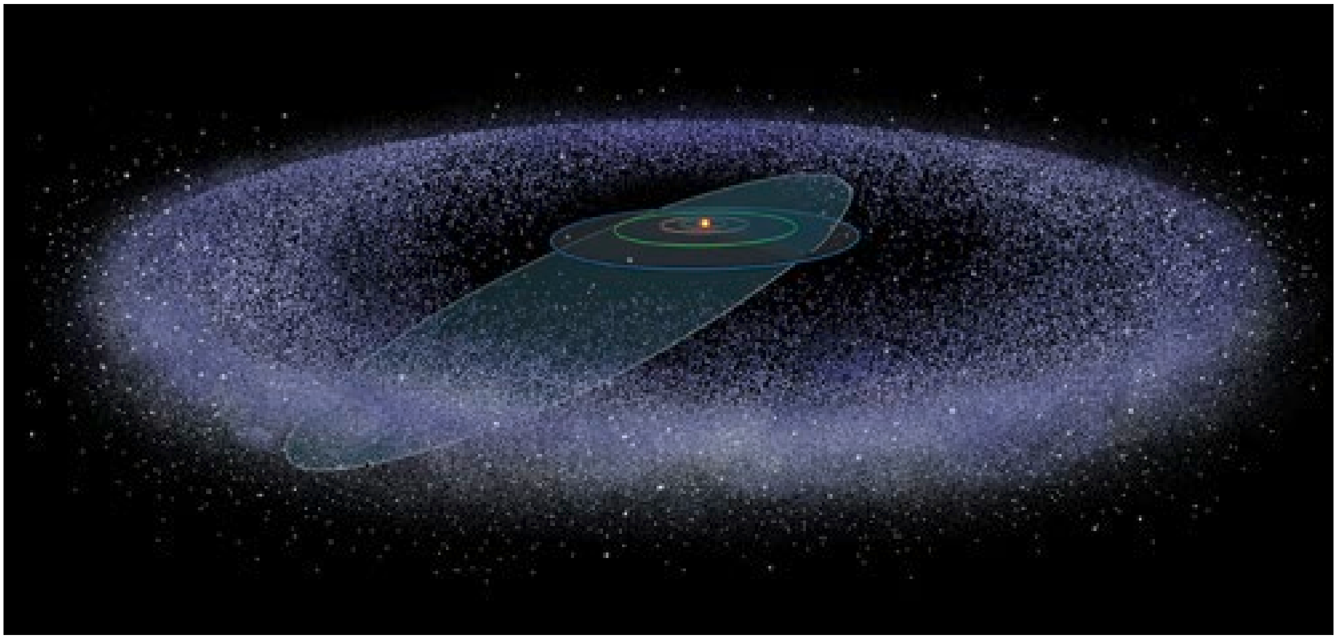


Image 35. Artist's rendering of the Kuiper Belt Credit: Don Dixon/ cosmographica.com.

Self-assessment

1. It is quite difficult to study the first stars with today's technology. What advantages does ALMA have for this research and why is it so important to study dust in space?
2. What are the advantages of ALMA's ability to study molecules for understanding the Universe?
3. According to current theory, how do planets form?
4. What question about the Sun could ALMA be central to answering?
5. Why is it important to study comets?

4. Activities

Antennas at the ALMA Array Operations Site. Photograph by Dave Yoder/National Geographic

Activity 1

Capture the invisible!

How do we get access to the Internet using Wi-Fi? How does your voice travel on a cellular phone call? The response in both cases is that we receive or send information using electromagnetic radiation. A radio telescope also captures this type of waves, but unlike these devices (artificial sources), it captures the waves generated by the stars and other stellar objects (natural sources).

OBJECTIVE: Identify the main parts of a radio telescope and their function.

DRAW

1. With a pencil, connect the dots in the correct order.

2. Identify the following parts of the drawing:

- Dish: reflects the radio waves on the receiver.
- Receiver: captures the radio waves.
- Support: maintains the receiver in the position of the focal point of the plate.

3. List three similarities between a radio telescope and a satellite TV antenna like the one installed on your house.

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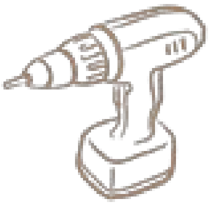
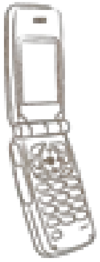
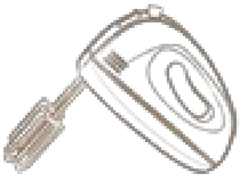
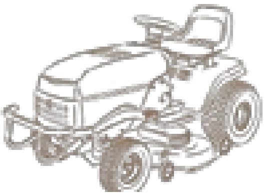
4. Circle the devices that use electromagnetic waves.









Activity 1
Capture the invisible! | Teacher's Note

This activity enables children to identify basic aspects of radio astronomy, a science that analyzes radio waves captured with a radio telescope. The radio telescope's antenna is configured by a series of components.

BACKGROUND INFORMATION

Radio telescopes function much like a radio, but because of the size of their reflectors, radio telescopes can detect very weak radio waves. The reflector or dish directs the radio waves towards the antenna. This effect is comparable to the way in which a common mirror reflects visible light. In optical telescopes, which detect visible light, normally there is a mirror that serves the same function as the reflector in a radio telescope.

Astronomers can "focus" on a specific celestial body to collect much more radiation from that body than could be captured without a reflector, using just the antenna. This enables them to detect even the weakest radio waves in space.

Radios, Wi-Fi signals, cell phones, and televisions, among others, use radio waves on different frequencies. These radio waves are invisible to the human eye.

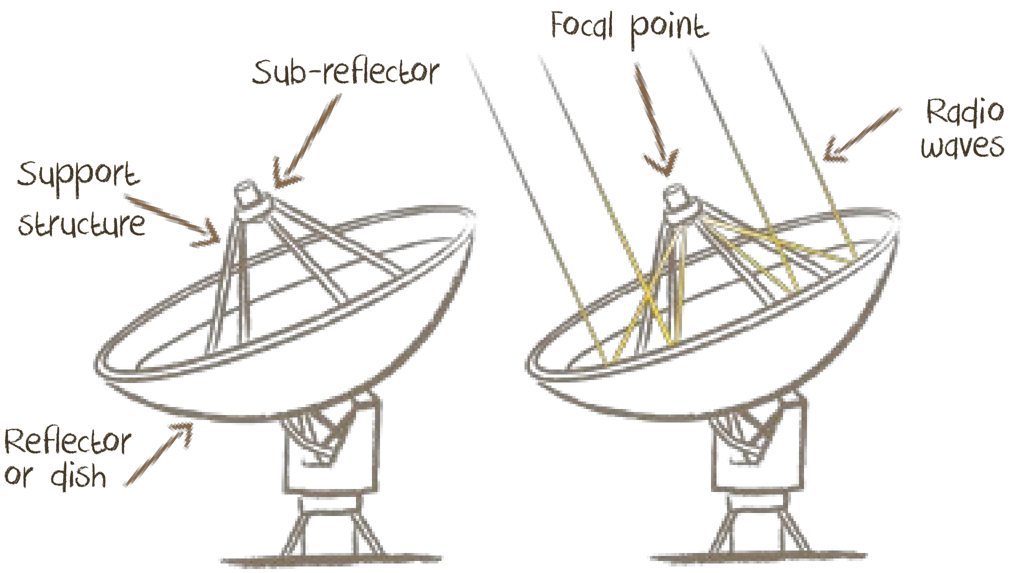
PREPARACIÓN

Print and copy an activity work sheet for each student.

Identify the images related to this activity. (Slides 1, 2 and 3)

IMPLEMENTATION

- Ask the students to connect the dots in the drawing.
- Ask them if they recognize what they have drawn.
- Explain that it is a radio telescope and write each of the key terms on the board.
- Ask them to complete the rest of the activities.
- Ask the students what they associate with radio telescopes and write their responses to create a conceptual map on the board. Ask them to copy the map in their notebooks. If the students don't understand how a conceptual map can help in their learning process, this is a good opportunity to show them.
- Television antennas capture signals from artificial sources (satellites) and their structure is similar to a radio telescope.
- You can ask the students to name other devices that use radio waves.



Activity 2

Did you hear that? Amplify sound with a paper cone

The radio telescope's dish works by reflecting the radio waves on a single point, known as the focal point. Sound waves can also be directed in such a way as to increase their volume. Do the following experiments and write the responses in your notebook.

OBJECTIVE: Understand how the parabolic antenna of a radio telescope works.

INCREASING THE VOLUME

Materials

- 1 sheet of paper

Procedure

- Do an experiment with a partner.
- Take a sheet of paper and roll it into a cone. Stand 2 meters away from your partner and say something to them through the cone.
- Now repeat it without using the cone.

Do you notice a difference?

AMPLIFYING THE SIGNAL

Procedure

- Choose a partner and sit 2 meters away from them. One of the two should read the text below to the other at a moderate volume:

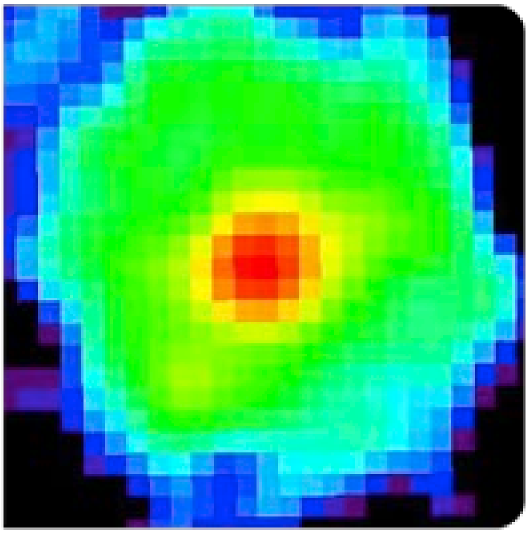
"You can hear high or low sounds. Sometimes you can't hear someone clearly and other times you can hear them perfectly."

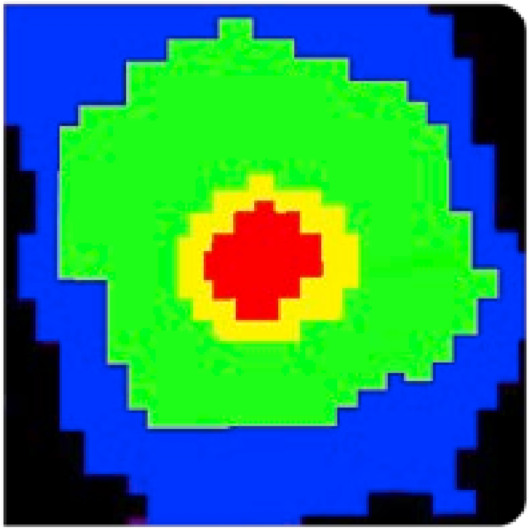
- Switch roles.
- Now repeat the experiment. While one person reads the other listens, but this time with their hands behind their ears. Make sure to read the text at the same volume as before.
- Now, switch roles again!

Do you notice a difference?

PARABOLIC ANTENNAS

Why do radio telescopes have that shape?





INCREASING THE VOLUME

Analyze

- Observe the images above.
- The first image shows the Arecibo radio telescope in Puerto Rico, which has a diameter of 305 meters.
- The second shows the 20-meter dish of a radio telescope.
- To the right are images of the same celestial body, but captured by each radio telescope.

Answer

What is the difference between the two radio images?

Which radio telescope do you think produces the best radio image?

Explain your answer, using the following concepts: reflector, surface, sensitivity, focal point.

Activity 2

Did you hear that? | Teacher's Note

This activity allows students to experience the effects of using a reflector to increase both the volume of their voices and the volume of the sound they hear.

OBJECTIVE: Understand how the parabolic antenna of a radio telescope works.

BACKGROUND INFORMATION

Our ears are also a type of reflector: They help capture sound waves and direct them toward our eardrums, which in this case would be our antennas. If we put our hands behind our ears, we can expand these "reflectors," thereby improving our hearing ability.

IMPLEMENTATION

1. Locate the section for this activity. Discuss the ways we can emit sounds at different volumes. (Slide 4)
2. Ask the students what they see in the image. Explain to them that a sound can be aimed in a specific direction with the help of a cone so the person it is directed at will hear the sound better.
3. Mention that before headphones and speakers existed, gramophones were used. Show them the image in the document. (Slide 5)
4. Ask the students to describe what they see in Slide 5. Explain to them that it is a gramophone that is used to amplify sound, just as the cones do.
5. Discuss the basic principle: The larger the cone, the greater the sound volume!
6. Explain that our ears work like inverted cones.
7. Explain that we hear sounds better when we put our hand behind our ears.
8. Explain that the shape of a radio telescope's reflector is similar to that of our ears.
9. Discuss the exercise and the fact that radio telescopes use the same principle: the larger the reflector, the greater the number of radio waves captured.

ANSWERS

1. Do you notice a difference?

The volume increases.

2. Do you notice a difference?

It sounds better.

3. Why do radio telescopes have that shape?

To capture the highest number of radio waves.

4. What is the difference between the two radio images?

The first has more details.

5. Which radio telescope do you think produces the best radio image?

The one with the larger reflector.

6. Explain your answer, using the following concepts: reflector, surface, sensitivity, focal point.

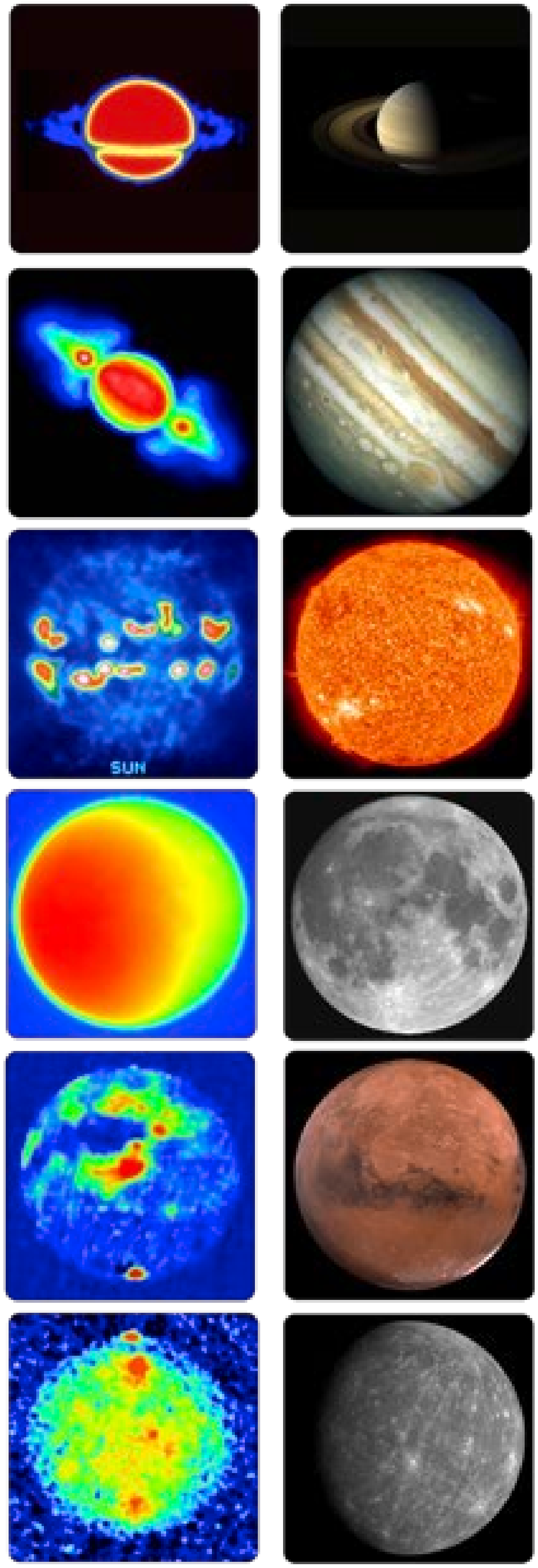
The larger the reflector, the more sensitive the radio telescope is to radiation coming from space. This is because the larger surface area of the reflector can reflect more radiation on the antenna's focal point. This increased sensitivity enables the radio telescope to capture dark objects in the Universe.

Activity 3

Create a radio image

The information received by a radio telescope is recorded and converted into a set of numbers that are then processed and turned into images.

OBJECTIVE: Understand how a radio telescope image is formed.



MATERIALS

- Colored pencils

BACKGROUND INFORMATION

It is impossible to directly show, in a photograph, the radio waves captured by radio telescopes. That's why astronomers color their radio images with colors that are "visible" to us.

In general, the process consists of pointing the radio telescope toward a precise point in the sky and record the signal coming from there. Then it is aimed at the immediately adjacent spot, storing the respective information. This is how a file is obtained that looks like the one shown on the next page.

The radio telescope scans the celestial object sequentially, receiving the radio waves from each small point in the space around the object. Some areas can have stronger radio waves than others. All the information about intensities is numerically associated with their respective position. For example, if the radio waves are weak in a particular position, a small numerical value will be recorded. If there are no radio waves coming from that point, the computer assigns a zero to it.

OBSERVE

The images show some space objects photographed with light that is visible and invisible to the human eye, respectively (radio waves). Different properties can be observed in each image. On the Moon, for example, darker gray areas can be seen with visible light, but they can't be detected using radio waves. Invisible (radio) light can be used to see Jupiter's magnetic field, which doesn't appear in the image to the right. Saturn's rings, meanwhile, are visible with both types of light.

1. Identify the objects shown in the images.
2. Discuss those that the students find most interesting.

Activity 3

Create a radio image

Color in an image according to the pixel value

Exercise 1. Color each "pixel" with the corresponding color:

0 = purple
1 = black
2 = light blue
3 = dark blue
4 = green
5 = yellow
6 = red

0	0	0	4	4	4	4	5	5	5	4	0	0	0	0	0	0	0	0	0	0	4	4	4	5	4	4	0	0	0	0
0	0	4	4	4	4	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	4	5	4	4	0	0	0
0	4	4	4	4	4	5	5	0	0	0	0	0	0	4	4	4	0	0	0	0	0	0	0	4	4	5	4	0	0	0
0	4	4	4	4	4	0	0	0	0	4	4	4	4	4	5	5	4	4	0	0	0	0	0	0	4	4	5	4	0	0
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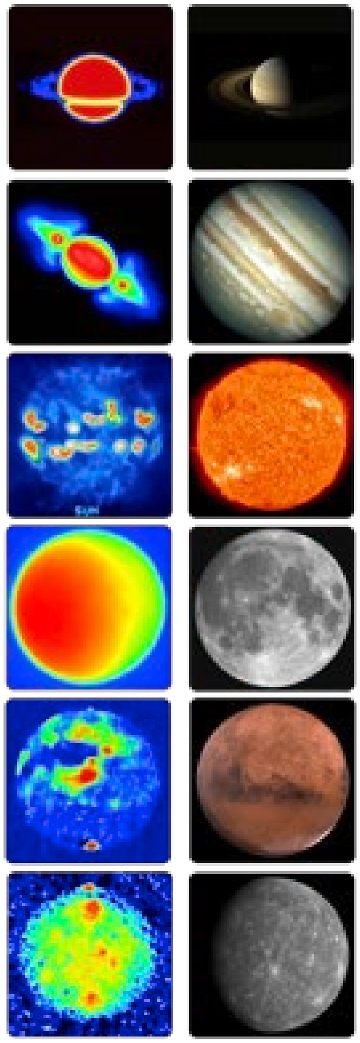
0	0	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	4	0	0	0	0	0

Activity 3
Create a radio image | Teacher's Note

The purpose of this activity is for the students to understand how radio telescopes gather information that is then used to generate an image. The process is explained in a simple way, leaving out various technical aspects.



MATERIALS

- Colored pencils
- One copy of the worksheet for each student

IMPLEMENTATION

Explain to the students the existence of visible and invisible light.

Explain to them that astronomers observe the sky using radio telescopes.

Ask them to complete Exercise 1 on the worksheet.

Once they have finished, discuss the exercise. Explain to them that they drew a radio image. Tell them that radio telescopes observe the Universe using a different light than we see, producing different kinds of images.

With the help of Slide 7, explain to students that there are different 'types of light' in the electromagnetic spectrum, such as infrared, X-ray or visible light.

Show them Slide 8 and explain to them that it is a radio image.

Explain to them why astronomers generate images with radio telescopes instead of using optical telescopes.

Ask them to describe the differences and similarities between the two types of images of the same object.

OBSERVE

In descending order, the objects that appear in the photographs are: Saturn, Jupiter, the Sun, the Moon, Mars, Mercury.

Saturn's rings are visible in both types of light. Meanwhile, on Jupiter one can observe radio emissions generated by intense currents in its magnetosphere.

COLOR IN EACH PIXEL

The resulting image is similar to the one shown below. Ask the students to say what they associate with the structure represented in the image, which is similar to a spiral galaxy.

Activity 4

Paper radio telescope | Make a radio telescope

Radio telescopes are like a giant radio, but unlike radios, they can focus on or aim at radio sources. Radio telescopes can change direction to observe different objects in the Universe. We do the same with our ears: The best way to hear a sound is to turn your head so your ear is pointing toward the source of the sound. While celestial bodies emit radiation as their temperatures (level of molecular agitation) change, objects on Earth emit sounds because they vibrate. These objects then cause the air to vibrate and we capture the vibrations with our ears.

OBJECTIVE: Identify the main parts of a radio telescope and their functions. Relate sound and electromagnetic waves through their basic properties.

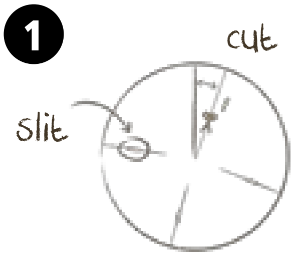
MATERIALS (per pair of students)

- scissors
- glue
- 2 toilet paper tubes
- pencils
- paper

PROCEDURE

1. Carefully cut out the disk at the end of this activity. Don’t forget to cut the slits! Follow the example.
2. Cut along the line with the scissors drawn in the illustration to the right. Apply some glue to the white strip and glue the two ends together, placing one on top of the other.
3. Make sure the lines are on the inside of the reflector.
4. To assemble the antenna: Cut out the figure below the dish.
5. Fold the cut-out backward along the dotted lines.
6. Apply glue to the antenna legs.
7. Insert the antenna legs in the slots and glue them to the other side of the reflector.
8. Glue the reflector to a toilet paper tube and you’re done! You’ve just made your own radio telescope!

❶



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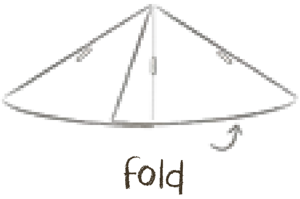

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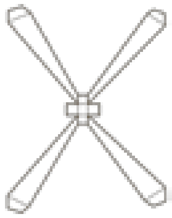

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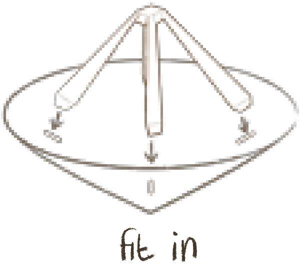

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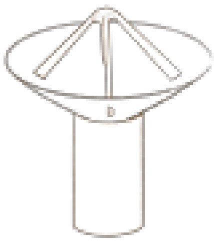
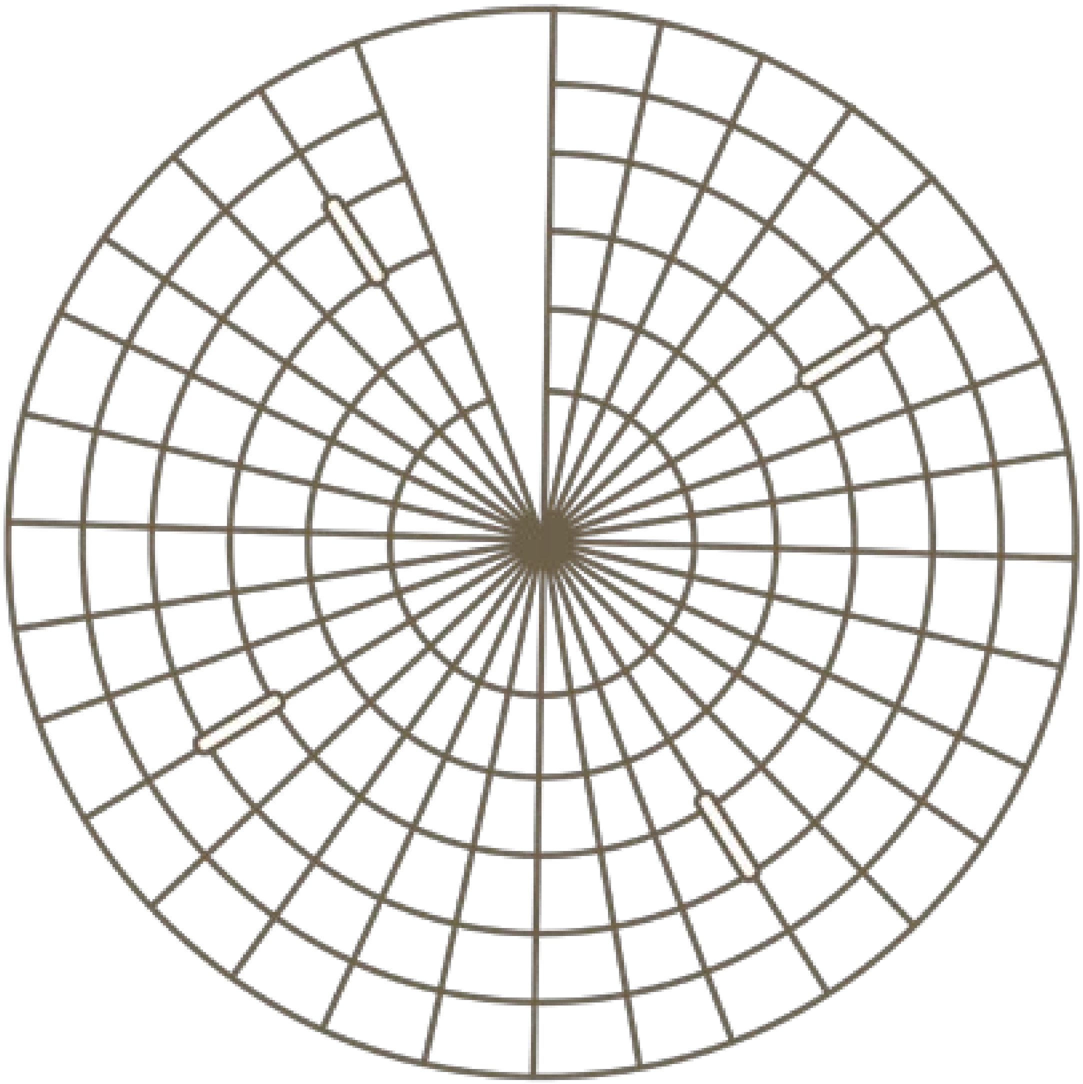
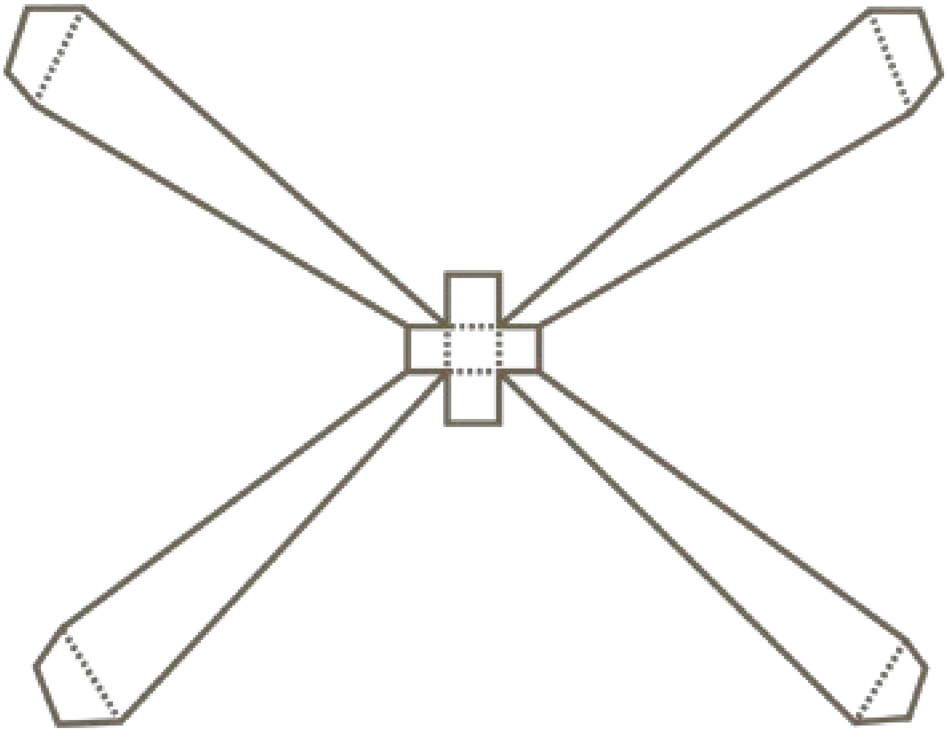






Activity 4

Paper radio telescope | Make a string telephone

Work in pairs to make a string telephone.

MATERIALES (per pair of students)

- 2 rigid plastic cups
- 4 meters of kite string
- 2 paper clips
- pencils

PROCEDURE

1. Use the pencil point to make a small hole in the bottom of each cup.
2. Pull the ends of the string through each of the holes. Tie each end of the string to a paper clip to prevent the string from coming out.
3. Use the cups like a telephone to talk to a classmate.
4. Make sure the string is stretched tight and taut.

While the behavior of the different kinds of waves is similar, in this experiment we use sound waves, while ALMA works only with electromagnetic wave receivers.

PREDICT

What do you think will happen when you speak into one of the ends?

……………………………………………………….…

……………………………………………………….…

VERIFY

What is the lowest sound volume that can be transmitted?

……………………………………………………….…

……………………………………………………….…

What is the impact of the string's tension?

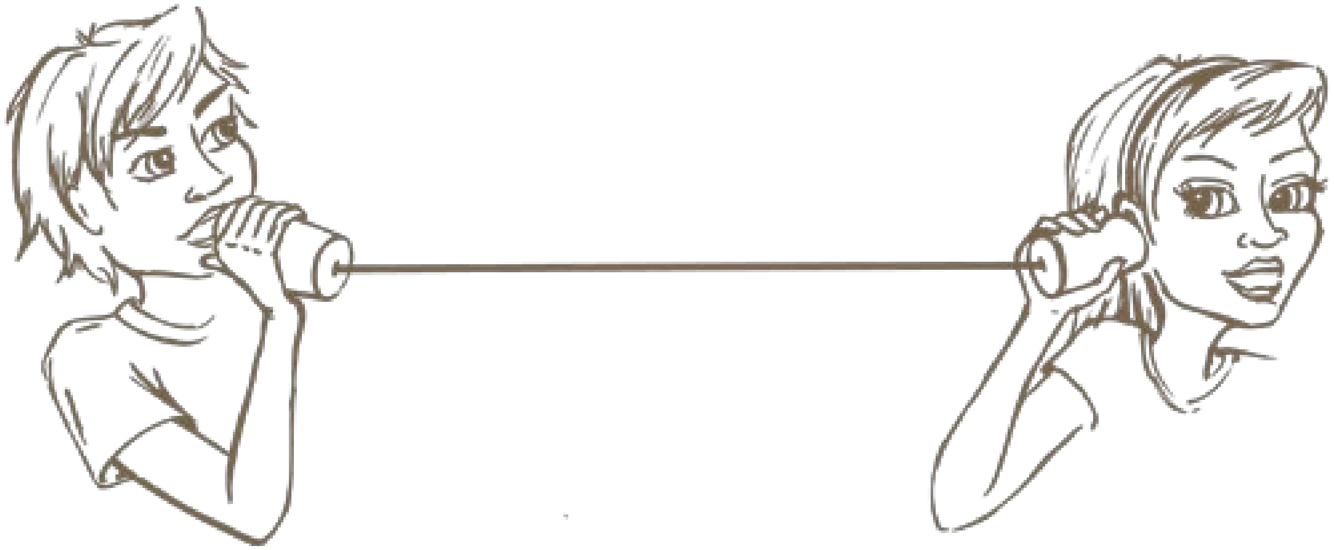
……………………………………………………….…

……………………………………………………….…

What purpose does the cup serve?

……………………………………………………….…

……………………………………………………….…



Activity 4

Paper radio telescope | Teacher's Note

This activity familiarizes the students with the shape of radio telescopes. They also learn that, in addition to air, there are other elements that transport sound.

BACKGROUND INFORMATION

This activity gives the students an opportunity to relate in a concrete way to the basic elements of a radio telescope.

The class can discuss in more depth the difference between the form of a cone such as the one they're using and a parabola like the dish of an ALMA antenna. For example, if the cone were covered with silver paper, the rays of light from the Sun would concentrate on its axis, unlike a parabolic reflector, which concentrates all the rays on the same point. In this sense, cones do not appear to be good reflectors.

When sound is emitted inside the cup, the waves cause the bottom of the cup to vibrate, transmitting the wave to the string. This wave travels through the string to the other cup, where the inverse process occurs: the vibration of the bottom of the cup is transmitted to the air and then to our ears.

When the string is not taut, the energy of the vibration dissipates and doesn't reach the other end.

PREPARATION

- Each student should have a copy of the activity worksheet and the sheet with radio telescope pieces.
- Ask the students to bring the materials in advance.
- It may be useful to punch the holes in the cups before beginning the activity.
- Show them slides 4 and 5 of the activity.

IMPLEMENTATION

- Ask the students to start the activity; those who finished first can help their classmates.
- When all the students have finished, ask them to describe what they did. Help them by asking if they know why there is a web-like structure on the antenna dish and what its function is. Explain to them that this is the sub-reflector, which redirects the signal captured by the dish toward the receivers of each antenna.
- Sound consists of waves of pressure that make the air vibrate. Show them by holding a sheet of paper and blowing on the edge, to produce a low sound. Explain that the piece of paper vibrates rapidly, causing the air around it to oscillate. This vibration reaches our ears, enabling us to hear sounds.
- Ask them to do the following activity.
- Discuss the activity. Explain to them that sound propagates not only through air but also through other elements such as water or string.
- Ask them about the tension of the string and the cups.
- If there is enough time, you can ask the students if it is possible to combine two telephones together. Before doing the experiment, ask them to predict what will happen.

Activity 5

Relationship between temperature and wavelength

Explore Wien’s displacement law

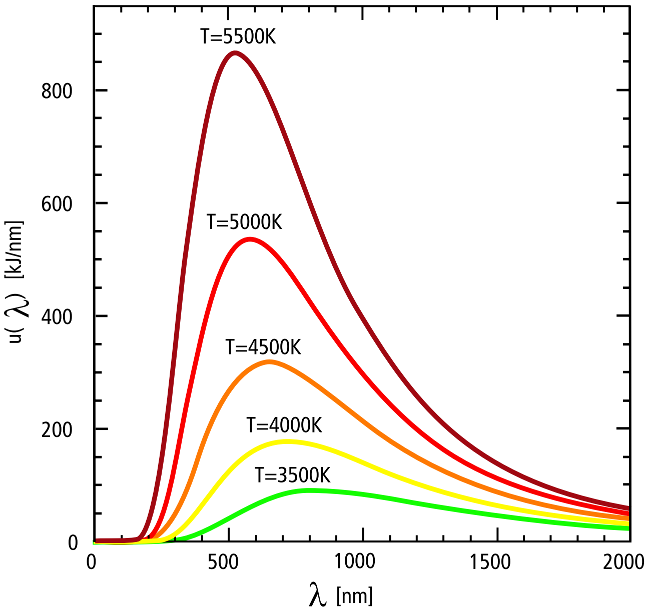
One of the most common processes that generates electromagnetic radiation is thermal radiation, which can be easily felt by placing your hand near a hot object. But this radiation can’t be seen with the naked eye. Its wavelength depends on the object’s temperature.

OBJECTIVE: Understand the relationship between the temperature and wavelength of the radiation emitted.

BLACK BODY RADIATION

A black body is an imaginary object that absorbs all incident radiation in all wavelengths and and it also emits radiation. Its maximum point of emission is given for a wavelength that depends solely on the temperature of the body.

As the temperature of the black body increases, the maximum emission point is displaced toward smaller wavelengths on its spectrum (higher frequencies). This explains why a piece of metal turns an incandescent red color (wavelengths around red) when it heats up. If the temperature continues to rise, it eventually becomes white (wavelengths near the midpoint of the visible range).



WIEN’S LAW

The maximum emission wavelength, λ_{max} of the distribution of a black body based on temperature T, is given by Wien’s displacement law:

$$\lambda_{máx} = \frac{b}{T}$$

where b = 2.897769 × 10–3 m·K is known as Wien’s displacement constant.

APPLY IT

1. How does maximum wavelength vary with temperature?
2. The maximum emission wavelength for the Sun’s radiation is in the range of light visible to the human eye. Is this a coincidence?
3. We can use Wien’s displacement law to calculate the wavelength of maximum emission for black body emissions from objects at different temperatures. Fill in the blank boxes in the following table:

Object	Temp.	Maximum wavelength
A star such as the Sun (surface)	5500 K	
Room temperature	300 K	
Dust clouds in interstellar space		0,15 mm

Activity 5
Relationship between temperature and wavelength
Teacher’s Note

This activity helps students understand the relationship between the radiation emitted by an object at a specific temperature and characteristic color (wavelength).

BACKGROUND INFORMATION

Black body radiation is the heat radiation emitted by an imaginary object, called a black body, that absorbs all the radiation it receives before re-emitting it. Various astronomical objects radiate with a spectrum similar to that of a black body at a given temperature.

The figure shows the Hertzsprung-Russell diagram, which summarizes all the current knowledge we have about stars. One of the things we can see is precisely the relationship between the temperature and color of a star. Thus, the surface of the Sun, with a temperature of 5,778 Kelvin, shines more intensely in those wavelengths that our eyes can see or interpret as yellow-green, and which correspond to about 502 nanometers (a figure 2,000 times smaller than a millimeter). The coldest stars look red and the hottest ones appear blue.

PREPARATION

Print and copy an activity worksheet for each student.

You can show to the students the Hertzsprung-Russell diagram from Slide 9.

IMPLEMENTATION

- Explain the main aspects of the Hertzsprung-Russell diagram shown in the document.
- Note that as the temperature of the object we want to study decreases to a few tenths of a Kelvin, the wavelength of maximum emission is found in the sub-millimeter/millimeter range.
- Some of the coldest objects in the Universe, such as giant clouds of dust and molecular gas where new stars form, have temperatures in this range. This explains why sub-millimeter astronomy is vital for studying wavelengths of maximum emission in which these clouds emit most of their thermal radiation.
- The ALMA radio telescope allows astronomers to study millimeter and sub-millimeter wavelengths. Ask the students to estimate the temperatures of the objects that can be observed.

ANSWERS

1. How does maximum wavelength vary with temperature?

It varies inversely with temperature. When the temperature increases, the wavelength of maximum emission becomes shorter.

2. The wavelength of maximum emission for the Sun’s radiation is in the range of light visible to the human eye. Is this a coincidence?

No, natural evolution has enabled human beings to adapt to an environment with abundant visible light.

3. Calculate the values in the table.

527 nm, 10 micrometers, 0,15 mm

Activity 6

Angular Resolution and Diffraction Limit

What level of fine detail can be detected?

The diameter of a telescope determines its resolution power. Light, whether passing through an opening, a lens, or being reflected by a mirror, scatters due to diffraction. This scattering places a fundamental limit on the fine details (small angles) that can be detected by the telescope.

RESOLUTION

The diameter of a telescope determines its resolution power. In the case of a telescope with a primary mirror of diameter D, operating at wavelength λ, its maximum resolution (expressed as an angle in radians) is given approximately by:

$$\boxed{\theta \approx \frac{\lambda}{D}}$$

Where the angle must be measured in radians instead of degrees. There are 2π radians in a circle, as opposed to 360 degrees. Therefore, to convert radians to degrees, you must multiply by 360/2π.

APPLY IT

1. How does the resolution of a telescope change as wavelength increases? What happens when the size of the telescope is increased?

2. If the distance from the Earth to the Moon is approximately 380,000 km and the diameter of the Moon is 3,500 km, what is its angular size in the sky in minutes of arc?

3. Calculate the limit (resolution) for some modern optical telescopes, as well as for the human eye and Galileo's original telescope. Use a visible light wavelength of 500 nm. Express your results in seconds of arc (arcseconds) in the table at the right.

4. What were the smallest details that Galileo was able to distinguish on the Moon using his telescope in 1609, assuming perfect optics? And what would those details be in the case of the Hubble space telescope?

5. What angular resolution would the Hubble space telescope have if it observed wavelengths of 1 mm?

6. Along with ALMA, the Chajnantor Plateau is also home to the Atacama Pathfinder Experiment Telescope (APEX). Its single main dish has a diameter of 12 meters, similar to an ALMA antennas, and it receives millimeter and sub-millimeter signals. What is its angular resolution at 1 mm wavelengths?

7. How big does a single antenna such as APEX have to be to equal the resolution of the Hubble space telescope in visible light, if APEX observes at wavelengths of 1 mm? Is this possible?

Object	Diameter	Resolution
Human eye	5 mm	
Galileo's telescope	1,5 cm	
Hubble space telescope	2,4 m	
VLT, ESO (one mirror)	8,2 m	

Activity 6

Angular resolution and the diffraction limit

Teacher's Note

This activity helps students understand the concept of telescope resolution and perform simple calculations for various devices.

PREPARATION

Review the document for teachers that comes with this manual and identify the images related to this activity (Slide 10).

IMPLEMENTATION

- Explain what diffraction is.
- Explain how diffraction affects telescope resolution.
- Give other examples where diffraction can be observed, such as sound waves.
- Once the students have completed the activity, it is helpful to discuss their answers.
- Explain how angles are transformed at distances; explain the units that appear.
- It may be helpful to have the students demonstrate their calculations to their classmates.

ANSWERS TO QUESTIONS ON THE PREVIOUS PAGE

1. Resolution worsens as wavelength grows, and improves with increasing telescope size.
2. 32 arcminutes.
3.

Object	Diameter	Resolution
Human eye	5 mm	21 arc sec
Galileo's telescope	1,5 cm	6,9 arc sec
Hubble space telescope	2,4 m	0,04 arc sec
VLT, ESO (one mirror)	8,2 m	0,01arc sec

4. Galileo: approximately 13 km.
   Hubble space telescope: close to 80 m.
5. 1,4 arcminutes.
6. 17 arcseconds.
7. 4.8 km, which would be impossible to build.

Activity 7

Using interferometry in radio telescopes

How can several antennas be combined to obtain an image?

Interferometry is a technique in which multiple individual telescopes are linked together and their signals combined to simulate the effect of a single, gigantic telescope.

OBJECTIVE: Understand what an interferometer like ALMA is.

INTERFERENCE

Interference is a phenomenon of waves themselves and consists of the combining of two or more waves at in the same point in space, resulting in greater intensity (constructive interference) or reduced intensity (destructive interference).

For this to occur, the waves must be lined up, that is, their crests and valleys must be in phase. Destructive interference occurs when at a certain point in space a valley is superimposed on a crest, while constructive interference occurs when the crests or valleys coincide.

ALMA IS AN INTERFEROMETER

The resolution of an interferometer like ALMA doesn't depend on the diameter of the individual reflectors but on the maximum separation between the antennas or baselines. The antenna signals are combined and processed by a supercomputer–the ALMA Correlator–to simulate the functioning of a single telescope.

Thus, the actual resolution of the telescope is given by:

$$\boxed{\theta \approx \frac{\lambda}{D}}$$

where B is the maximum separation (or "baseline") between each telescope in the group. In the case of ALMA, we refer to a single dish as an "antenna" and to the entire array as the "telescope."

ALMA has 66 giant antennas with diameters of 12 and 7 meters distributed over the Chajnantor Plateau (altitude: 5,000 meters). The greatest distance, or baseline, is 16 kilometers between the antennas that are furthest from each other.

APPLY IT

1. If ALMA's antennas are distributed over 16 kilometers, what is its resolution when observing wavelengths of 1 mm?
2. How does this compare to the resolution of the Hubble space telescope at visible wavelengths?
3. Investigate how the antennas are moved into position for different configurations (www.almaobservatory.org)

ALMA antennas on the Chajnantor Plateau. Credit: ALMA (ESO/NAOJ/NRAO), O. Dessibourg.

Activity 7
Using interferometry in radio telescopes
Teacher's Note

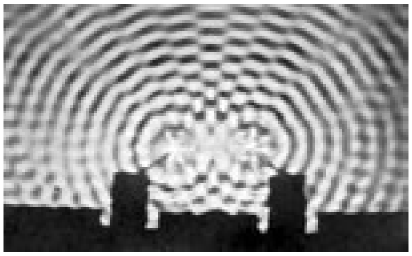
This activity will introduce students to the interferometry technique and help them understand one of ALMA's key characteristics.

PREPARATION

Identify the images related to this activity. (Slides 11 to 14)

MATERIALS

- Portable radio
- Remote control
- Cellular phone



DEMONSTRATION

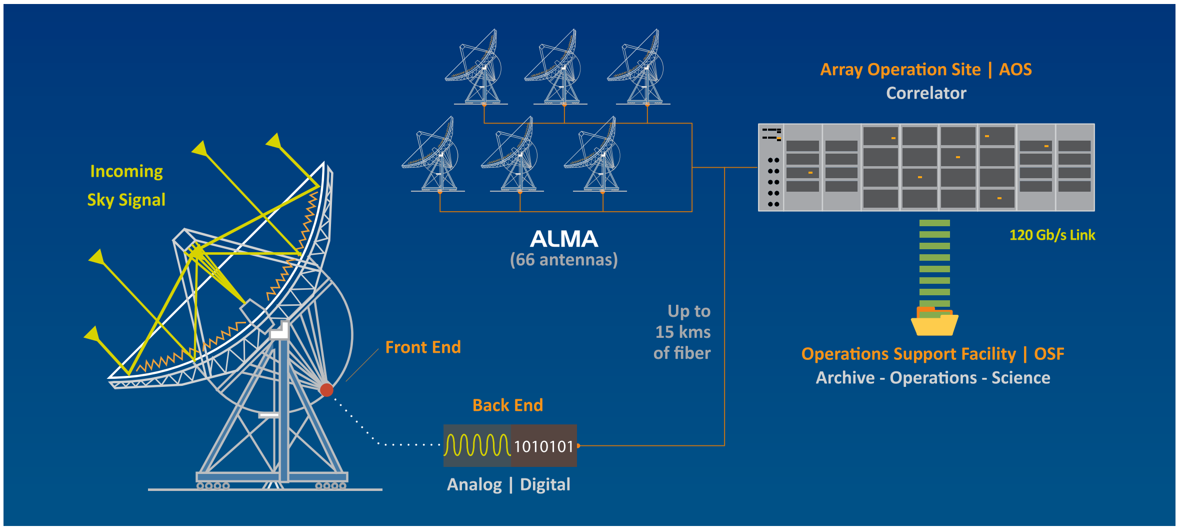
- Ask the students to name some devices that use radio waves.
- Explain to them that astronomers use radio telescopes to capture radio waves from space.
- Demonstrate that some devices use the same type of radiation as radios, showing them how to generate interference in a radio signal.
- Turn on a portable radio and ask them to listen closely to what happens when you press a button on the remote control.
- Because remote controls use infrared radiation (rather than radio waves), there is no interference.

IMPLEMENTATION

- Explain what interference is. Consider the two definitions in the text. You can do the following activities:
- Use a basin with water or a laser passing through a double slit (Slides 11 & 12).
- Once the students have completed the activity, it is helpful to discuss their answers.

ANSWERS TO QUESTIONS ON THE PREVIOUS PAGE:

1. 0,013 arcseconds.
2. The resolution of the Hubble space telescope is better at visible wavelengths.
3. Using two trucks designed especially for this task. Their names are Otto and Lore.



Activity 8

Variation of atmospheric pressure with altitude

Learn to calculate the height scale

At very high altitudes, atmospheric pressure is lower than at sea level, as is the amount of oxygen available. In this activity, we look at how atmospheric pressure at the ALMA site compares to sea level and other high-altitude places.

OBJECTIVE: UUse a simple model to study variation in atmospheric pressure at high altitudes.

CHAJNANTOR PLATEAU

ALMA's Array Operations Site (AOS) is located at an altitude of 5,000 meters above sea level on the Chajnantor Plateau. Conditions there can be optimal for sub-millimeter astronomy, but they are quite difficult for working and living. Because of this, daily operations are conducted at a site 2,900 meters above sea level, where the Operations Support Facility (OSF) is located.

ATMOSPHERIC PRESSURE: AN ISOTHERMAL MODEL

We can use a simple model to study how atmospheric pressure decreases with altitude, assuming that pressure decreases exponentially as altitude increases. This model is called "isothermal" since we assume that the air temperature remains constant. This is not totally accurate, but it is a reasonable approximation.

If p represents pressure as a function of altitude h above sea level and p_0 is the pressure at sea level (in other words, h = 0 meters), then,

$$p(h)=p_0e^{-h/H}$$

where H is the altitude where the pressure has fallen by a factor of 1/e (approximately 37%) and this is known as the atmosphere's height scale.

At sea level, the atmospheric pressure is close to 100 kPa and the height scale is approximately 8,400 meters.

APPLY IT

- The height scale can be calculated for different places that don't necessarily correspond to 8,400 meters. For example, at the summit of Mount Everest, with an altitude of h = 8,848 meters, the pressure measured is approximately 33 kPa. What is the height scale in this case?
- Considering a height scale of 8,400 meters, estimate the atmospheric pressure at the geographic altitudes of ALMA's OSF and AOS sites. Compare the atmospheric pressure at ALMA's AOS and sea level.
- The amount of oxygen available is related to atmospheric pressure. What is the approximate percentage of oxygen at sea level that is found at ALMA's AOS? Investigate the risks of working in conditions with little oxygen.

ALMA in solitude. Credit: ESO/B. Tafreshi (twanight.org).

Activity 8
Variation of atmospheric pressure with altitude
Teacher's Note

In this activity, students use a simple model to estimate the variation of atmospheric pressure with altitude. The activity introduces the concept of height scale and its dependence on the place where the model is used.

PREPARATION

Identify the images related to this activity. (Slides 15, 16 and 17)

Visit the "Location" section on the ALMA website (www.almaobservatory.org/) and verify access on Google Maps to the sites named.

IMPLEMENTATION

- Explain what the ALMA telescope's AOS and OSF are, show them the geographic sites on Google Maps or ask the students to find them, identifying the latitude, longitude and altitude.
- Together with the students, summarize the main characteristics of the atmosphere. Define the pressure unit Pa=1N/m2
- Explain the model's equation. Emphasize the importance of the number e in mathematics and science and why it appears frequently in different natural processes.
- Explain the significance of 1/e in general as 37% of the initial value.
- Discuss with the students to what point it seems reasonable to consider an isothermal model.
- Ask them to perform the applications. Define the limits of the research but expressly state what reliable sources they should use and ask the students to list those sources in their work.

THE EARTH'S ATMOSPHERE

The atmosphere is the layer of gas that surrounds Earth and is retained by gravity. It is made up of several gases, mostly nitrogen, oxygen, carbon dioxide and water vapor.

The atmosphere has several layers. The troposphere, which contains most of the atmosphere's mass (75%), is located below 11,000 meters. In this layer, temperature decreases with altitude.

In general, the pressure depends on temperature and altitude. But pressure data observed can be appropriately illustrated with a isothermal model. In an isothermal model, the average temperature considered is 300 K, which is consistent with several observations. Clearly, this model doesn't explain the -6.5ºC/km temperature variation in the troposphere, so the model needs to be refined.

ANSWERS

1. What is the height scale H in this case?

In this case the height scale for Mount Everest is 7,980 m.

2. Estimate the pressure at each site.

The pressure at OSF is 71 kPa and 55 kPa at AOS. Atmospheric pressure at the AOS is almost half of atmospheric pressure at sea level.

3. What is the percentage of oxygen?

It is almost half of all the oxygen available at sea level. At extreme altitudes, there is a risk of altitude-related illness, and even a risk of death. Because of this, ALMA workers only go to the Array Operations Site (5,000 meters above sea level) when strictly necessary.

Activity 9

Observing through the atmosphere

Identify the factors that influence opacity / transparency

ALMA was built at an altitude of 5,000 meters on the Chajnantor Plateau, in the Chilean Andes. The ALMA location in the Atacama Region has the altitude and aridity necessary for sub-millimeter astronomy.

OBJECTIVE: Identify the factors that affect the opacity of the atmosphere for certain wavelengths.

OBSERVING THROUGH THE ATMOSPHERE

Electromagnetic radiation's ability to pass through the Earth's atmosphere depends to a great extent on its wavelength. This is measurable in terms of atmospheric transparency or opacity. An opacity of 100% corresponds to 0% transparency and vice versa. At an opacity of 100%, radiation is completely blocked, while at an opacity of 0%, radiation is fully transmitted.

The atmosphere doesn't just absorb the weak signals from space that astronomers attempt to capture using ALMA; it also emits radiation itself.

The main factor for ALMA wavelengths is water vapor. That's why a location in a dry place at high altitude is so important. The amount of water vapor is usually measured in millimeters of "precipitable water vapor" (PWV), which is the depth of the pond that would form in a place if all the water were precipitated as rain.

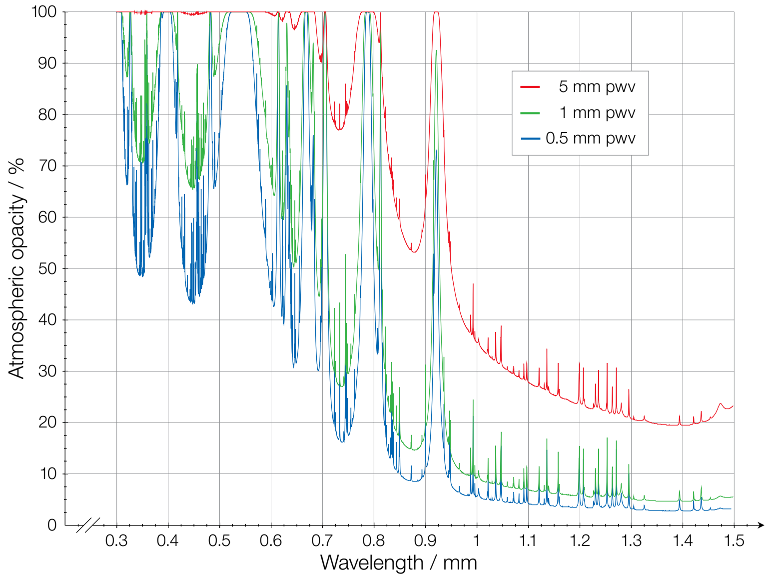
The average PWV value on our planet is close to 2.5 cm, but extremely dry conditions are needed for sub-millimeter astronomy.

On the Chajnantor Plateau, from April to December the median precipitable water vapor is approximately 1 mm, and it can even fall below 0.5 mm under particularly dry conditions.

APPLY IT

Refer to the graph to answer the questions:

1. How does opacity change as the amount of water vapor increases?
2. How does opacity change, in general terms, as the wavelength becomes shorter?
3. At longer wavelengths, such as 1.2 mm, why is it so critical to have lower levels of water vapor? It can be useful to compare what percentage of light is transmitted (take 100% and subtract the percentage of opacity) at 5 mm PWV and 0.5 mm PWV. What happens at shorter wavelengths, such as 0.35 mm?



Activity 9

Observing through the atmosphere

Teacher’s Note

EIn this activity, the students will recognize the importance of the water vapor factor in atmospheric opacity and its relationship to the wavelength of radiation observed from an object in the Universe.

PREPARATION

Identify the images related to this activity. (Slides 18 and 19)

IMPLEMENTATION

Show the students the image in the Slide 18. Analyze the information that it includes: wavelength and opacity. Ask questions such as: Which wavelength is more opaque or transparent? In what range do you find the greatest transparency?

Discuss the second illustration and ask the students to identify the variables.

The students can then do the exercises and discuss the results.

ANSWERS

1. How does opacity change as the amount of water vapor increases?

The opacity increases.

2. How does opacity change, in general terms, as the wavelength becomes shorter?

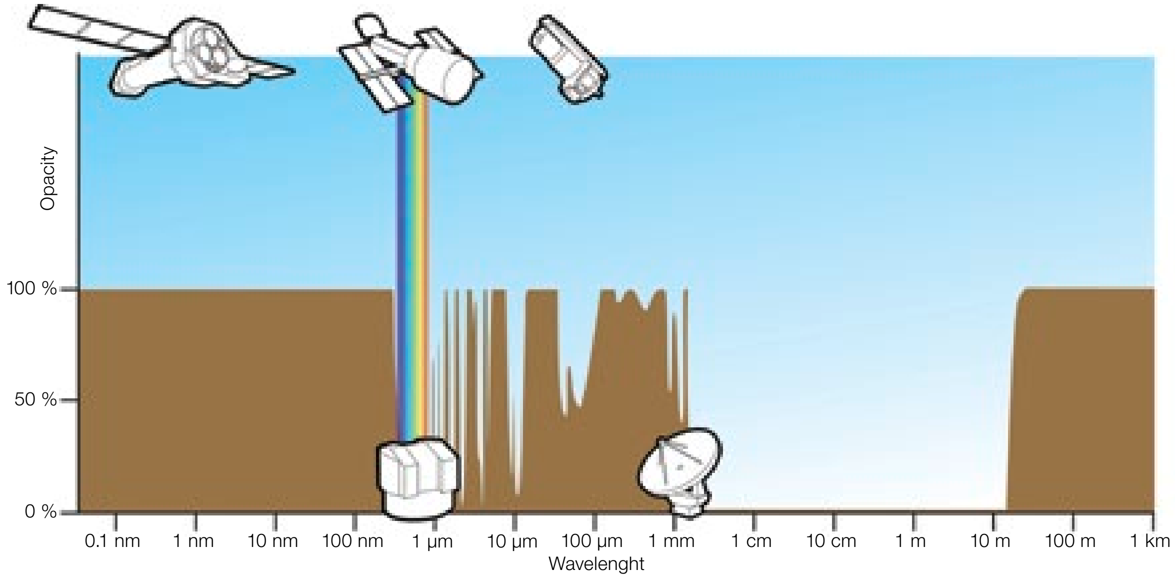
The opacity increases (although there are “windows” or zones of the spectrum where opacity is not so high).

3. Why is it so critical to have lower levels of water vapor? What happens at shorter wavelengths, such as 0.35 mm?

At shorter wavelengths, it is critical to have low levels of water vapor. At longer wavelengths, opacity is relatively low, even with high levels of water vapor.

ATMOSPHERIC OPACITY

In the image below, the level of the brown curve represents the opacity of the atmosphere at a given wavelength. The largest windows are at visible wavelengths (marked by a rainbow) and at radio wavelengths from approximately 1 mm to 10 m. ALMA operates in an extreme region, where opacity depends heavily on the altitude and aridity of the place.



Activity 10

The law of reflection

The dish of a radio telescope has a certain shape so that it can direct the waves captured on a specific point, known as the focal point.

OBJECTIVE: Apply the law of reflection to flat mirrors to explain the existence of a focal point in a parabolic mirror

FLAT MIRRORS

On a flat mirror, the angle of incidence is equal to the angle of reflection, measured from the normal, which is the line perpendicular to the mirror's plane (see top image at right).

MATERIALS

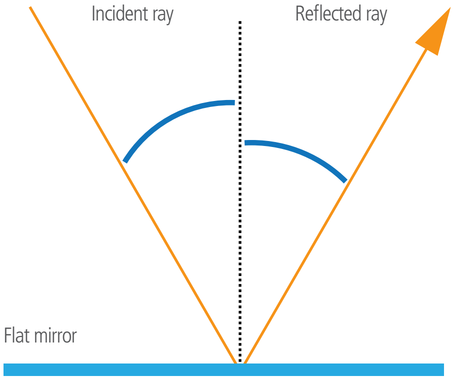
- 7 small mirrors (2x3 cm)
- A piece of high-density styrofoam, letter size
- Plasticine
- Scotch tape
- 15 pins

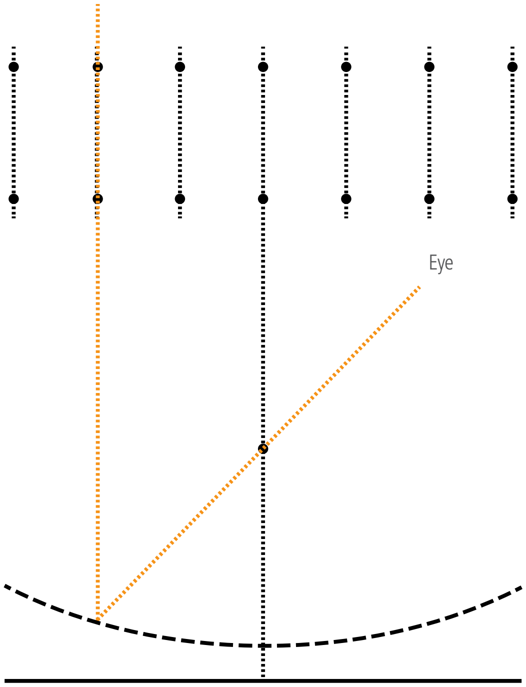
PROCEDURE

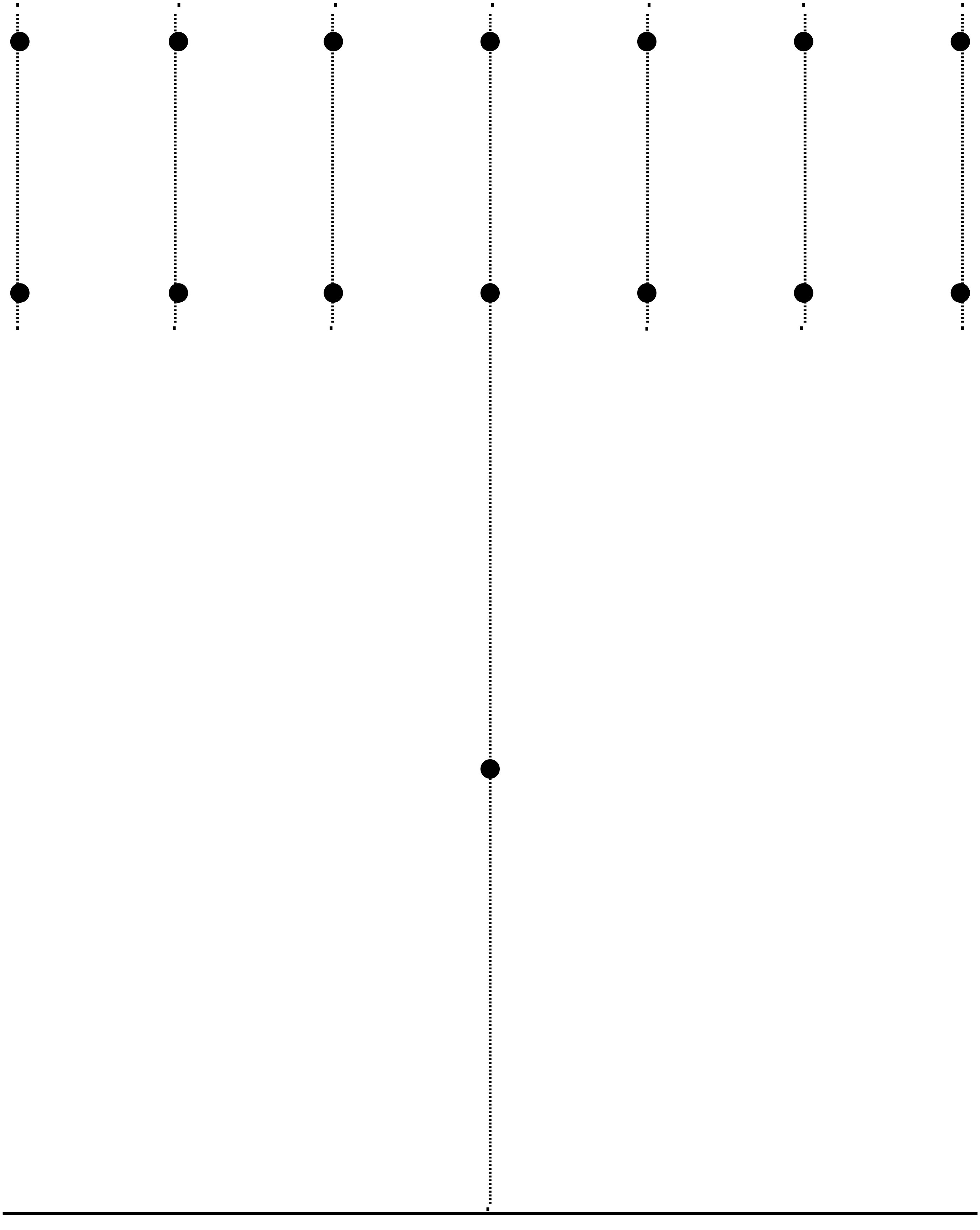
1. Print copies of the bottom image at right (use the one on the following page) and distribute them to the students. Ask the students to place the image on the styrofoam to make a base.
2. Insert the pins in the points marked on the paper.
3. Using a piece of tape on the opaque side of the mirrors, join them together.
4. Put a piece of plasticine on each mirror, so that they stand up vertically on the base.
5. Turn each of the mirrors so the central pin obstructs the other two.
6. Carefully draw a line on the paper that passes through the mirrors.

ANSWER

1. Where is the focal point?
2. Verify that the line drawn is a parabola.
3. What is the difference between having several flat mirrors and a single parabolic mirror?
4. Discuss a procedure to design a parabola that can be used to build an antenna with a diameter of 2 meters.







Activity 10
The law of reflection | Teacher's Note

In this activity, the students apply the law of reflection to understand how a parabolic mirror works.

PREPARATION

Gather the necessary materials. The recommended size of the mirrors is 2x3 cm; if that size is not available, the pattern will need to be adapted. The students can do this activity individually or in pairs.

IMPLEMENTATION

- Hand out the work guide and materials.
- Demonstrate the law of reflection; a laser pointer may be useful for this.
- Verify that the students do all required steps; assist them to ensure that the curve obtained is a smooth one.
- Discuss the answers with the class. Motivate them to come up with creative yet practical solutions for carrying out the procedure in question 4.

ANSWERS

1. Where is the focal point?

On the central pin.

2. Verify that the line drawn is a parabola.

The distance between the focal point and the mirror is measured and compared to the distance between the mirror and the guideline measured across the dotted line.

3. What is the difference between having several flat mirrors and a single parabolic mirror?

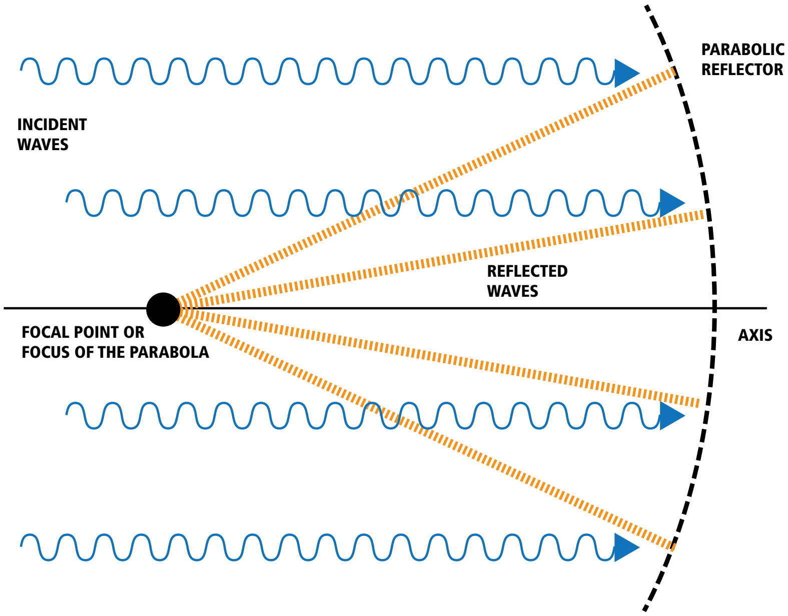
Flat mirrors reflect light in the same direction as the beam of incident light. On the contrary, parabolic mirrors converge the incident light to a single point, whose direction is different than that of the incident light.

4. Discuss a procedure to design a parabola that can be used to build an antenna with a diameter of 2 meters.

The process is based on the definition of a parabola; the students are expected to be able to define the technical aspects of building the parabola.

PARÁBOLA

This is the geometric place of the points on a plane that are equidistant from a given line, known as a guideline, and from a point external to it, known as the focal point. (Slide 20)



5. Glossary

An ALMA antenna on the road to the Chajnantor Plateau. Credit: ALMA (ESO/NAOJ/NRAO), R. Bennett.

Antenna

Metal device used to emit or capture radio waves. Antennas for radio telescopes such as ALMA capture only radio waves. They come in different shapes and are used by a variety of devices such as cellular phones, radios, television, wireless Internet, and others.

Astronomical unit (AU)

Unit of length that corresponds to the median distance between the Earth and the Sun. It is approximately equivalent to 150 million kilometers.

Color

This is the visual perception generated in the human brain upon interpreting nerve signals from the photoreceptors located in the retina, which detect and distinguish the diverse wavelengths of the visible spectrum.

Constellation

In astronomy, a constellation is a grouping of stars that is established by arbitrary or cultural conventions. Most human civilizations have grouped stars and given them names based on their myths or beliefs. The best-known constellations come from ancient Greece and represent various myths.

Ecliptic

The ecliptic is the apparent path of the Sun on a celestial sphere. It is an apparent movement, since it is the Earth that moves around the Sun. Its name comes from the Greek ἐκλειπτική (ekleiptiké), related to eclipses.

Ecliptic plane

The ecliptic plane is the median plane of the orbit of the Earth around the Sun. The plane of the Earth’s equator is inclined 23° 27’ with respect to the ecliptic plane.

Electromagnetic radiation

See definition of electromagnetic wave.

Electromagnetic wave

Electromagnetic waves are waves that do not need a material medium to propagate. In a vacuum, all electromagnetic waves propagate at a constant speed of 300,000 km/s, regardless of the speed at which the source generating them is moving. Electromagnetic waves include visible light, radio waves, X-rays and gamma rays, among others. The waves are produced by the accelerated movement of charged particles, which generate an electric field that is propagated in space.

Focal point

Radio waves from a specific celestial object are redirected by a radio telescope’s reflector towards its focal point, where the receiver that captures the waves is located.

Frequency

Frequency is the number of times that a wave oscillates in a unit of time. It is related to wavelength based on the following formula: frequency = speed of light / wavelength. In other words, the longer the wavelength, the lower the frequency, and vice versa.

Frequency band

These are intervals of the electromagnetic spectrum that are determined by their frequencies. They have a specific use in radio communications, and this is regulated by the International Telecommunication Union, which defines common uses of the bands such as broadcasting or mobile telephones. For example, the VHF (very high frequency) band from 30 to 300 MHz is used for FM radio, television, cellular phones and also for ham radio. Another band is UHF (ultra high frequency), from 300 to 3000 MHz, which is where you find microwave ovens, radio astronomy, wireless networks and Bluetooth, among others. ALMA functions in the EHF (extremely high frequency) band and the THz (Terahertz frequency) band. At ALMA, observations are conducted in 10 bands of different frequencies.

Gamma rays

Electromagnetic radiation of very high penetration and shorter wavelength than visible light. Gamma rays are usually produced by the disintegration of radioactive elements, but also by subatomic processes. Gamma rays are considered an ionizing radiation, because they can cause serious damage to cells and particularly to their nuclei. Most gamma rays produced in space are absorbed by the upper atmosphere before reaching the Earth's surface.

Hertz

This is a unit of frequency in the International System that is equivalent to one cycle of each second that passes. 1GHz = 10^9 and 1MHz = 10^6 cycles per second.

Hertzsprung-Russell diagram

Usually abbreviated as the H-R diagram, it describes the relationship between the absolute magnitude and temperature of a star. Developed by astronomer Ejnar Hertzsprung in 1905 and independently by Henry Russell in 1913, the diagram is used to study stellar evolution.

Isothermal

This refers to a body at a stable and uniform temperature.

Jansky (Jy)

This is the unit of density of spectral flux density, which is named for Karl G. Jansky and is equivalent to 10E-26 W/m^2.Hz. This unit is not part of the International System of Units. It is used to measure electromagnetic radiation from point sources and in the field of radio astronomy. To have a notion of this unit, the brightest radio sources in the sky have densities from 1 to 100 Jy.

Kelvin (K)

Absolute unit of temperature. The size of the unit is equivalent to one degree Centigrade, while its zero is equivalent to -273.5ºC. With Kelvin, the degree symbol º is not used, nor does it change in plural form, for example: 100 K.

Kuiper's Belt

This is the name of the set of bodies that orbit around the Sun at a distance between 30 and 50 astronomical units. Their existence was predicted by Gerard Kuiper in 1960 and the objects that comprise it have diameters between 1 and 3,000 kilometers.

Lorentz force

This is the force exerted by the magnetic field B on a charged particle that moves at a velocity v. The force is perpendicular to the plane formed by the vector of the magnetic field and the velocity, whose module is determined by the following expression: $F=qvB \operatorname{sen}(\theta)$, where θ is the angle of the velocity and the field B. This implies that the magnetic force on a stationary charge or a charge moving parallel to the magnetic field is zero. The direction of the force is obtained from the right hand rule or the right-handed screw: using the right hand, the fingers close up rotating the vector speed toward vector B, where the thumb provides the direction of the force.

Meridian

Meridians are maximum semicircles on the Earth's surface that pass through the North Pole and the South Pole. They are imaginary lines used for finding locations on the Earth's surface and determining the time zone. Because they are referential, it was necessary to establish a prime meridian, and since 1884, the prime meridian is the one that passes through the observatory in Greenwich, near London. The "local meridian" is the one passing through the place where the observer is located.

Microwave

Microwaves are electromagnetic waves in the range of 300 MHz to 300 GHz. They encompass the UHF, SHF and EHF radio frequency bands. In addition to communications, microwaves are used every day to heat food with some water content, since microwaves with frequencies of 2.45 GHz can stimulate these molecules, increasing the temperature of the food.

Milky Way

The spiral galaxy containing the Solar System. It is estimated to have close to 300 billion stars and has a diameter of 100,000 light years. According to diverse observations, its morphology corresponds to a barred spiral. The Milky Way is part of the Local Group, a group of galaxies and other objects linked by the force of gravity and which includes, among others, the Andromeda Galaxy, the Triangle Galaxy, the Magellanic Clouds, the M32 and M110 galaxies, as well as other smaller systems.

Nanometer

This is a unit of length equivalent to one billionth of a meter ($1 \text{ nm} = 10^{-9} \text{ m}$).

Optical radiation

See definition of visible light.

Pulsar

A pulsar or pulsating star is a neutron star that rotates, emitting a beam of electromagnetic radiation. This radiation can only be observed when the beam is pointed towards Earth, just as the beam of a lighthouse can only be seen when it is pointing in the observer's direction. This is what makes the radiation emitted appear to pulsate. The first pulsar was discovered by Bell and Hewish in 1967 and the signal detected had a period of almost 1.33 seconds. These scientists initially believed they had discovered the existence of extraterrestrial beings, so they called this source LGM (for Little Green Men).

Pressure (Pascal, kPa)

This is the physical magnitude that measures the force applied per unit of surface. In the International System, pressure is measured in pascals (Pa), a unit that is equivalent to 1 Newton acting uniformly on 1 square meter. The kPa, which is equal to 1,000 Pa, is also commonly used.

Quantum

From the Latin term "quantum": quantity of something, it corresponds to the minimum unit of magnitude or a minimal variation in the beginnings of quantum theory. According to this theory, electric charge is quantized, since the measurement of all charges corresponds to an entire quantity of the charge on an electron.

Radian

This is the unit used to measure an angle in the International System of Units. It is calculated as the angle that subtends an arc of circumference equal to the radius of the same.

Radio astronomy

The study of the Universe through analysis of radio waves rather than visible light. Radio astronomy is conducted using radio telescopes, which can detect radio waves.

Radio source

An object outer space (such as stars, galaxies or dust) that emits electromagnetic radiation in the region of radio waves. These objects are studied in radio astronomy. In 1931, Jansky was the first to detect these waves coming from the center of the Milky Way.

Radio telescope

Radio telescopes capture radio waves from the Universe. While optical telescopes (designed to study visible light) are equipped with a lens, radio telescopes have a reflector. The reflector redirects radio waves from space toward the receiver located at the center of the radio telescope.

Reflector

The reflector is the part of the radio telescope that reflects the radio waves from the Universe onto the receiver located at its center.

Short-wave band

The short-wave band has a frequency between 3 and 30 MHz. Used mainly by radio stations that broadcast internationally, these waves are reflected by the ionosphere.

Stefan-Bolztmann law

A law that relates the temperature of the surface of a body to the energy it radiates.

Telescope

Optical instrument for observing distant objects, particularly objects in the sky.

Visible light

Visible light is the part of the electromagnetic spectrum that can be seen with the human eye. It contains all the colors of the rainbow.

Wavelength

Wavelength is the distance between two crests of an electromagnetic wave. Its value is related to frequency: the greater the frequency, the shorter the wavelength. The following formula is used to calculate wavelength:

wavelength = speed of light / frequency.

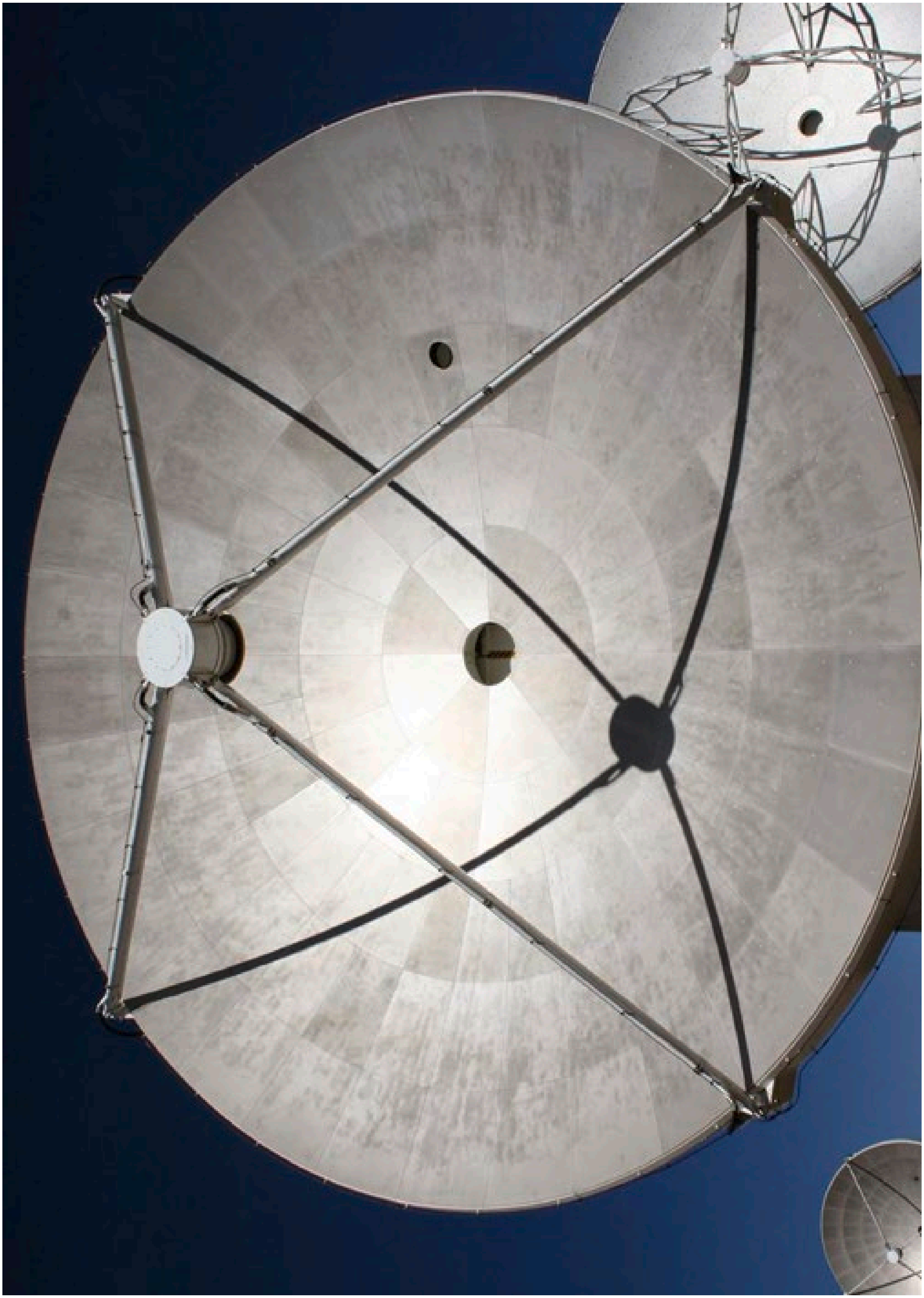
Wien's law

Law that relates temperature to the wavelength at which the maximum radiation of a black body is emitted.

X-rays

Radiation similar to gamma radiation, but with a longer wavelength. X-rays are also considered ionizing radiation because their high penetration can cause significant damage to living tissue.

6. Slides



Slide 1 | Reflector

The most visible part of each antenna is the reflector (also known as the dish or plate). At ALMA, most of the reflectors have a diameter of 12 meters. The reflectors perform the same function as a mirror in an optical telescope: to capture radiation from distant astronomical objects and direct it towards a receiver that measures the levels of that radiation.

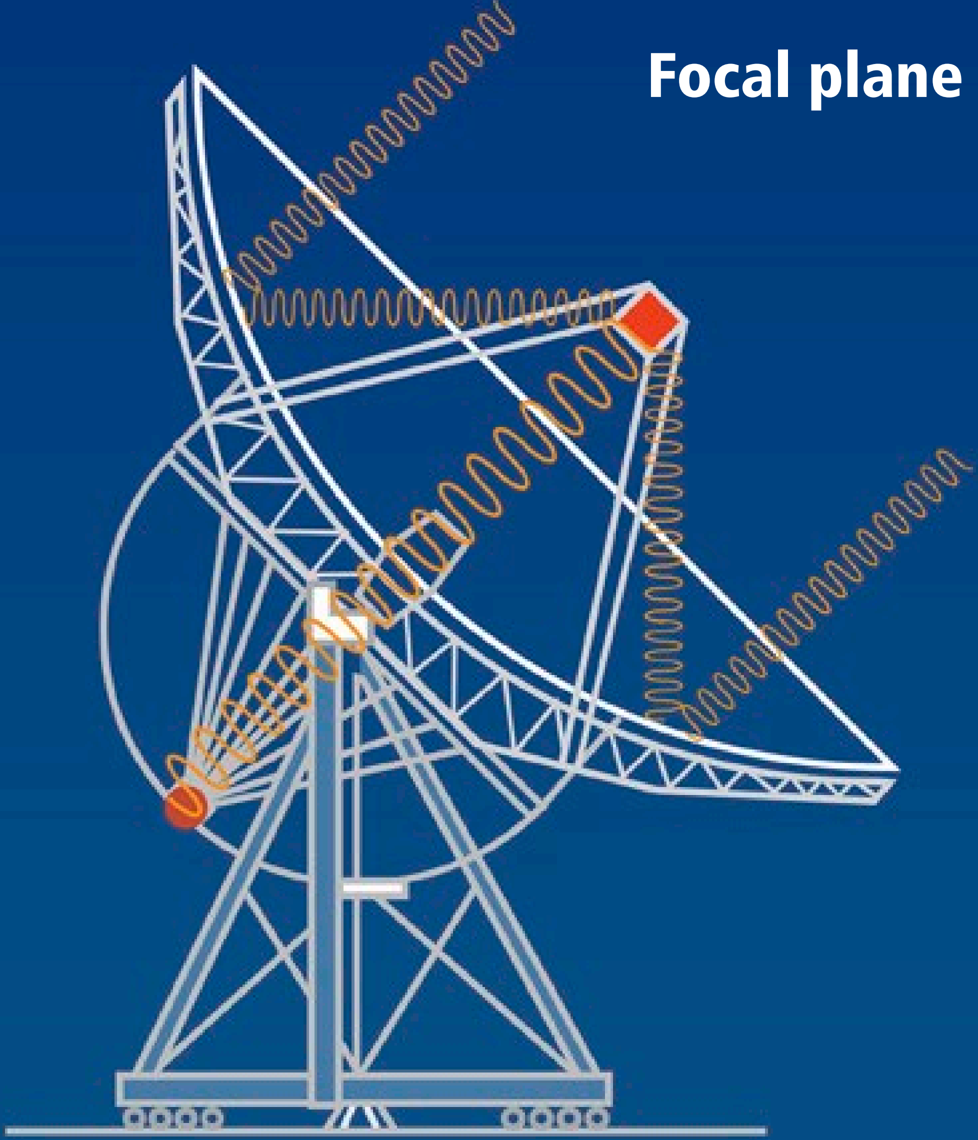
Credit: ALMA (ESO/NAOJ/NRAO).

Slide 2 | Reflector

ALMA reflectors are metal panels rather than mirrors, due to the wavelength for which they are designed. The reflective surfaces of any telescope must be practically perfect, since any slight imperfection greater than the wavelength to be captured prevents the microscope from obtaining the correct data. Since ALMA antennas detect longer wavelengths than visible light, while they have a precision of up to 25 micrometers (much less than the thickness of a sheet of paper), they don't need mirror reflectors. Therefore, although ALMA reflectors appear to be giant satellite receivers, for a photon with sub-millimeter wavelength (light particles) they are almost perfect and very precise reflective surfaces.

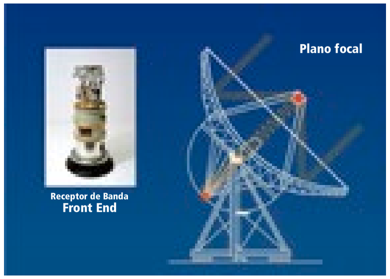
Credit: ALMA (ESO/NAOJ/NRAO).

Band receiver
Front End



Slide 3 | Front End

The ALMA Front End system is the first element in a complex chain of signal reception, conversion, processing and recording. The Front End is designed to capture signals from 10 different frequency bands.



ALMA's Front End is far superior to any existing system. In fact, products derived from the ALMA prototypes are leading to improved sensitivities in millimeter and sub-millimeter observatories around the world. The Front End units are made up of numerous elements produced in different parts of Europe, North America, East Asia and Chile.

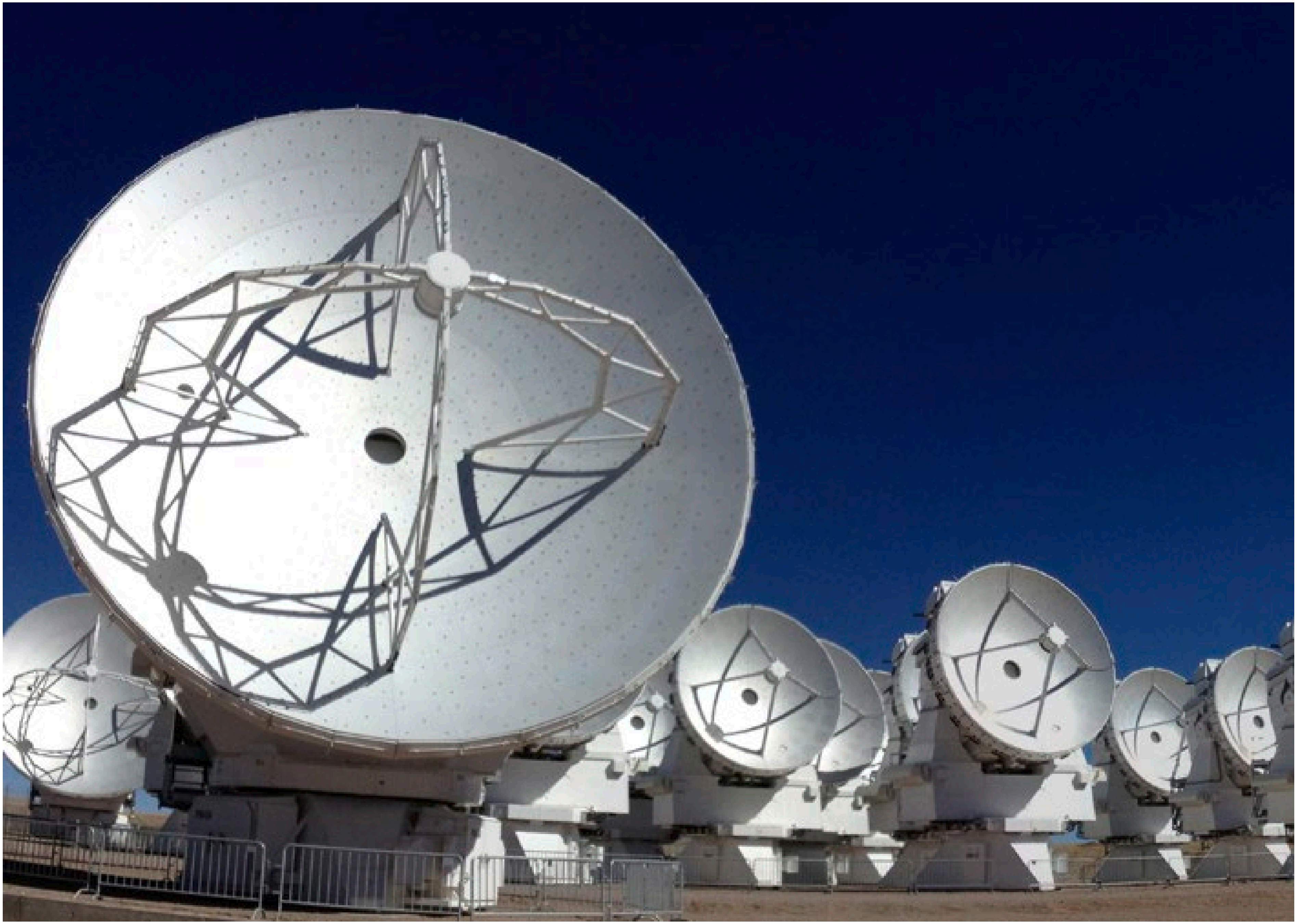
Credit: ALMA(ESO/NAOJ/NRAO).

Slide 4

Credit: Wikimedia commons

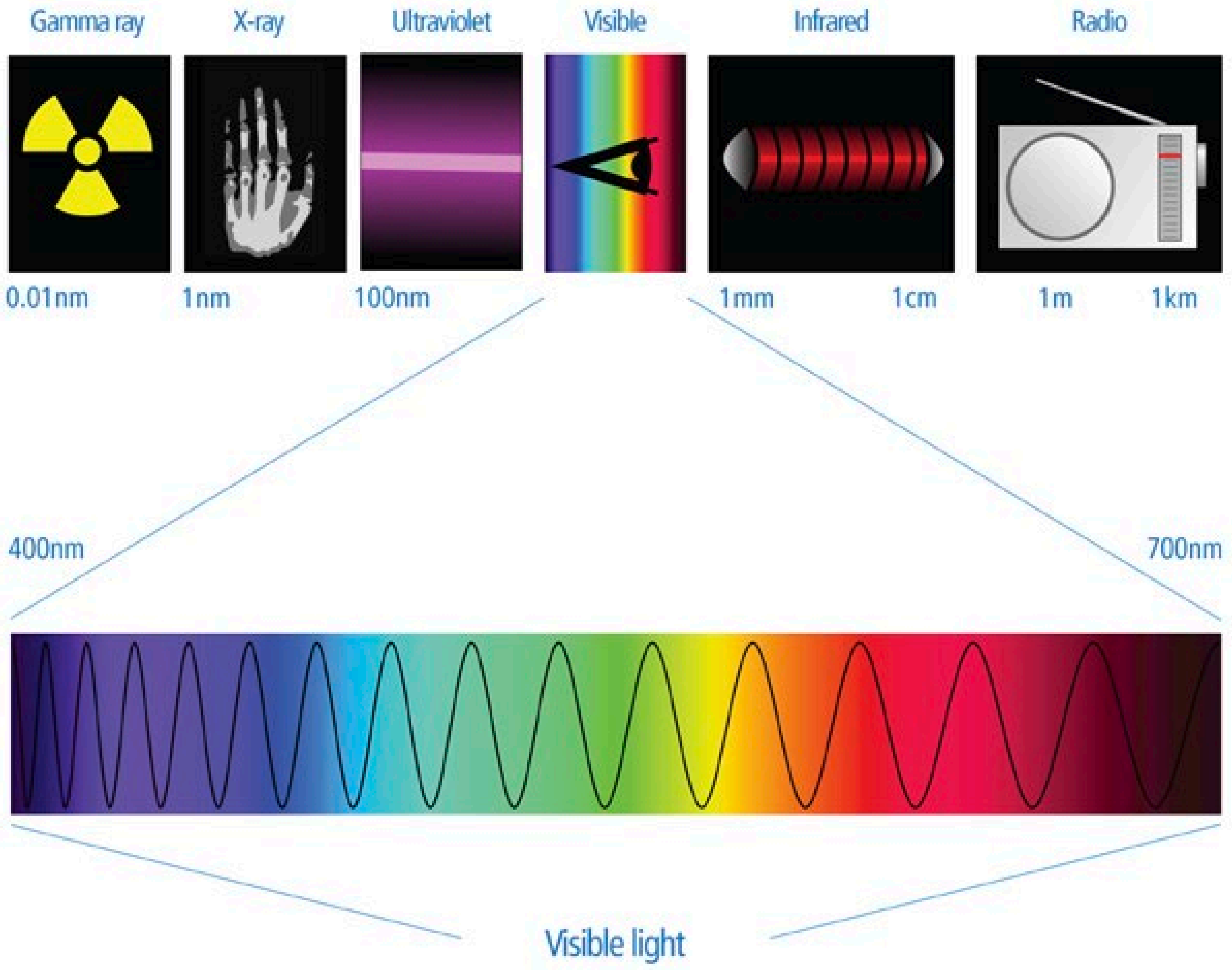
Slide 5 | Gramophone

Credit: Wikimedia commons



Slide 6 | ALMA Antennas

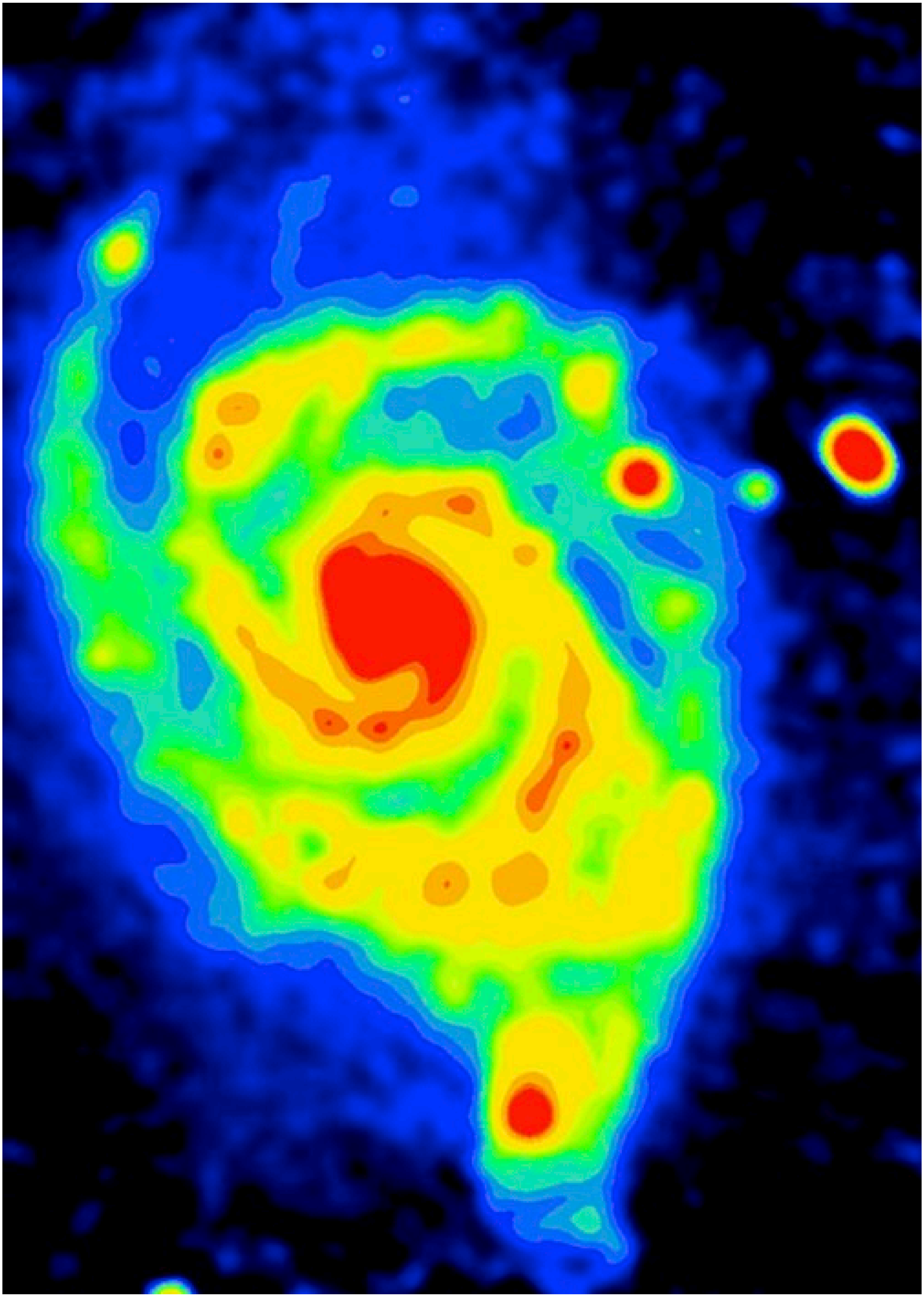
Credit: ALMA (ESO/NAOJ/NRAO).


Gamma ray
X-ray
Ultraviolet
Visible
Infrared
Radio
0.01nm
1nm
100nm
1mm
1cm
1m
1km
400nm
700nm
Visible light

Slide 7 | Electromagnetic Spectrum

Electromagnetic spectrum, showing the optical or visible range and applications for various wavelengths.

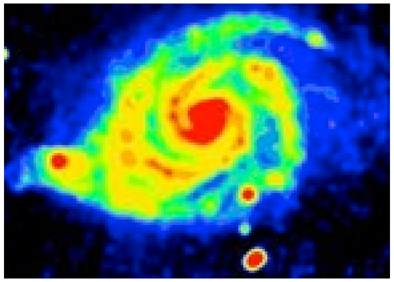
Credit: Tatoute. License: GNU..

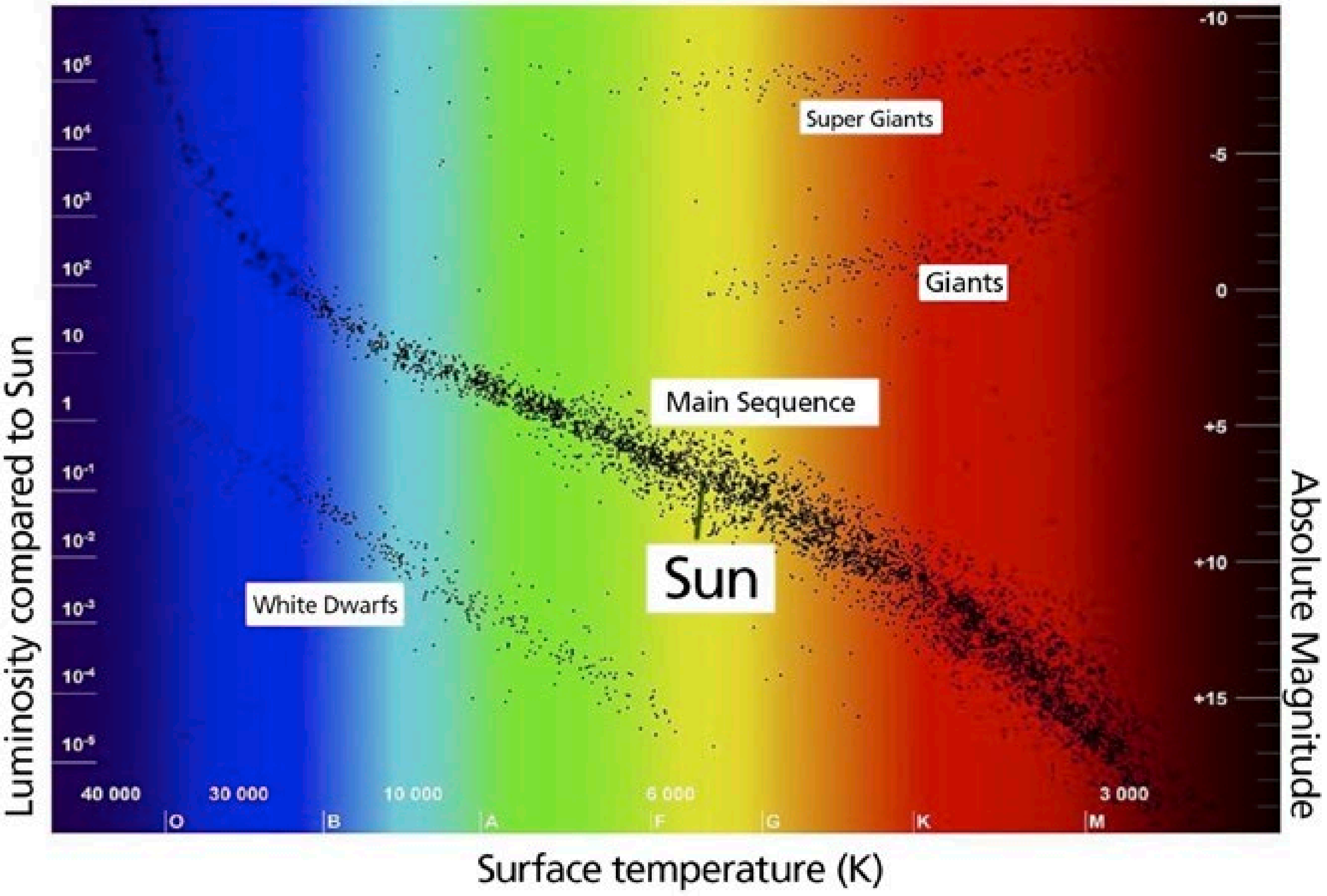


Slide 8 | Spiral Galaxy

Image of a spiral galaxy taken in the X-ray range.

Credit: NASA/Chandra.

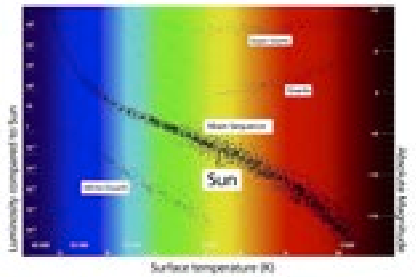



Luminosity compared to Sun
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Absolute Magnitude
-10
-5
0
+5
+10
+15
Super Giants
Giants
Main Sequence
Sun
White Dwarfs
40 000
30 000
10 000
6 000
3 000
O
B
A
F
G
K
M
Surface temperature (K)

Slide 9 | Hertzsprung–Russell Diagram

The figure shows the Hertzsprung-Russell diagram, which summarizes all the knowledge we have about stars today. One of the things we can see is precisely the relationship between the temperature and color of a star. Thus, the surface of the Sun, with a temperature of 5,778 Kelvin, shines more intensely in those wavelengths that our eyes can see or interpret as yellow-green, and which correspond to about 502 nanometers (a figure 2,000 times smaller than a millimeter). The coldest stars look red and the hottest ones appear blue.

Credit: ALMA (ESO/NAOJ/NRAO).



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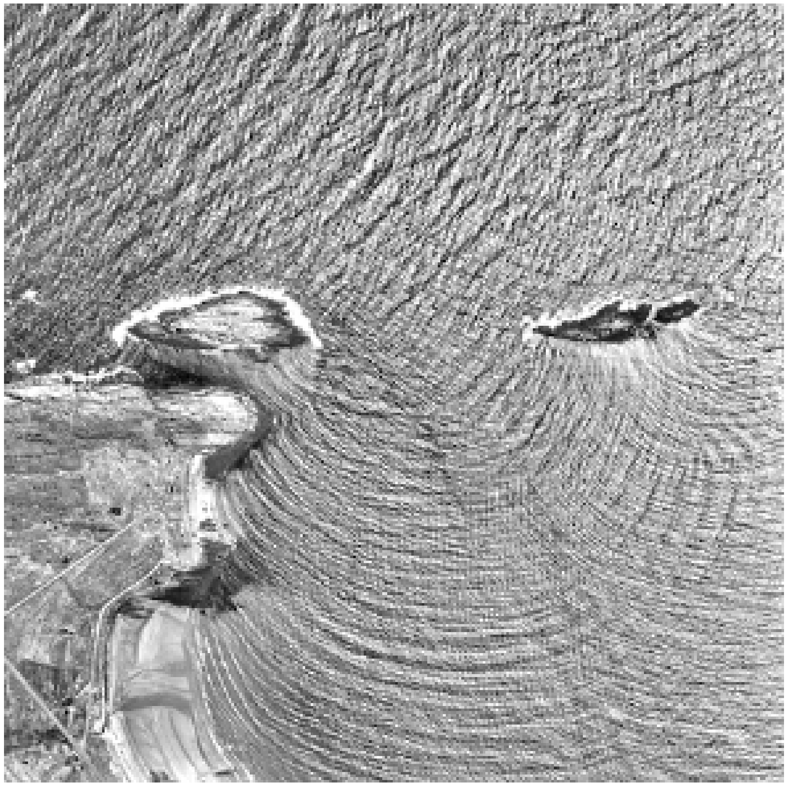

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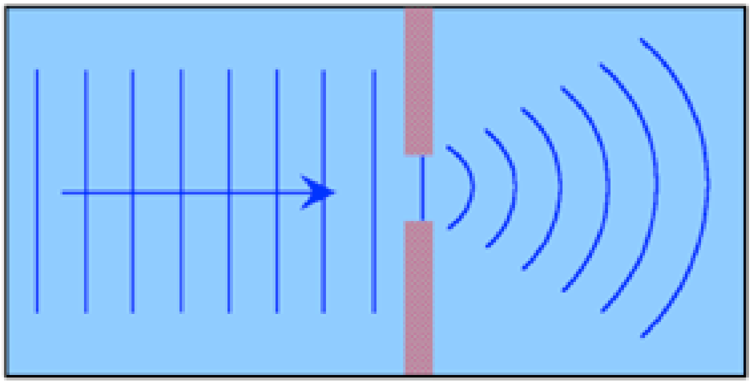


3

Slide 10 | Wave Diffraction

1. Aerial image of ocean waves hitting obstacles.

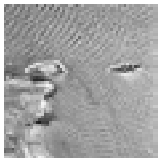
2. Diffraction of flat wavefront by a slit, showing how the wave changes shape.

3. Variations of combinations of wavefronts hitting an obstacle, showing the effects of the size of the slit on the diffraction effect.

Credit:

1. http://www.gcsescience.com/Diffraction-Water-Waves.gif

2. http://johnvagabondscience.files.wordpress.com/2009/03/diffraction.jpg



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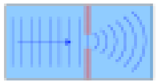

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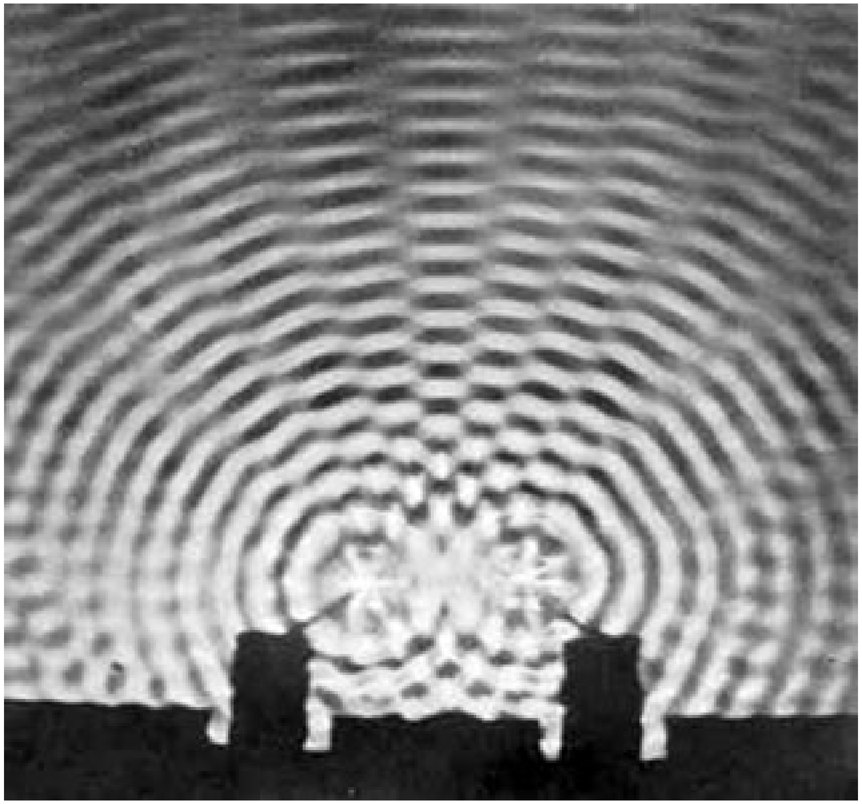
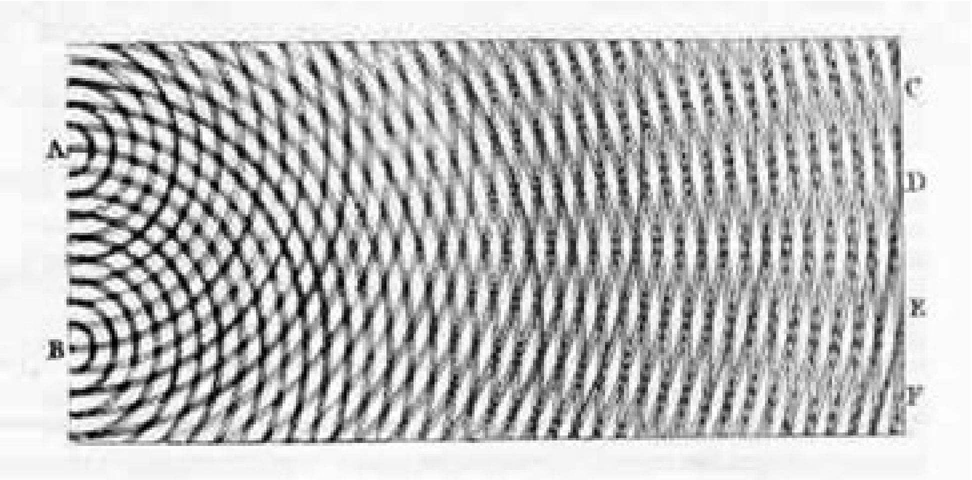
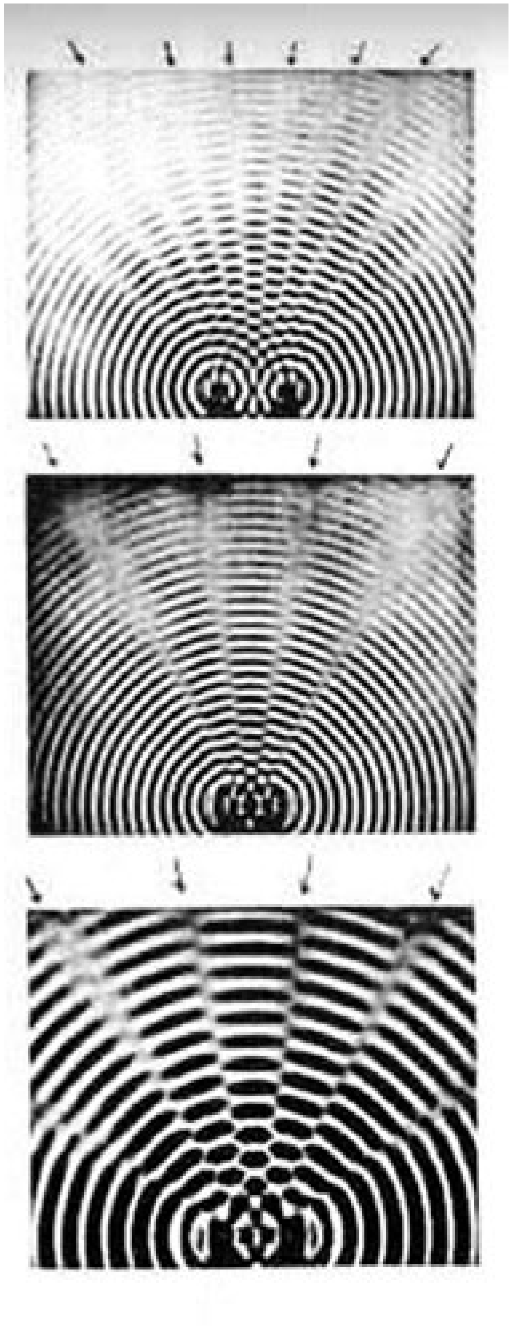
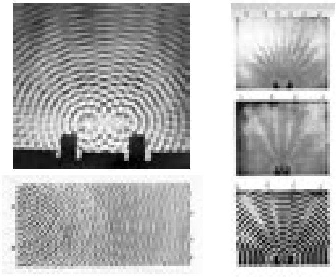



A
B
C
D
E
F



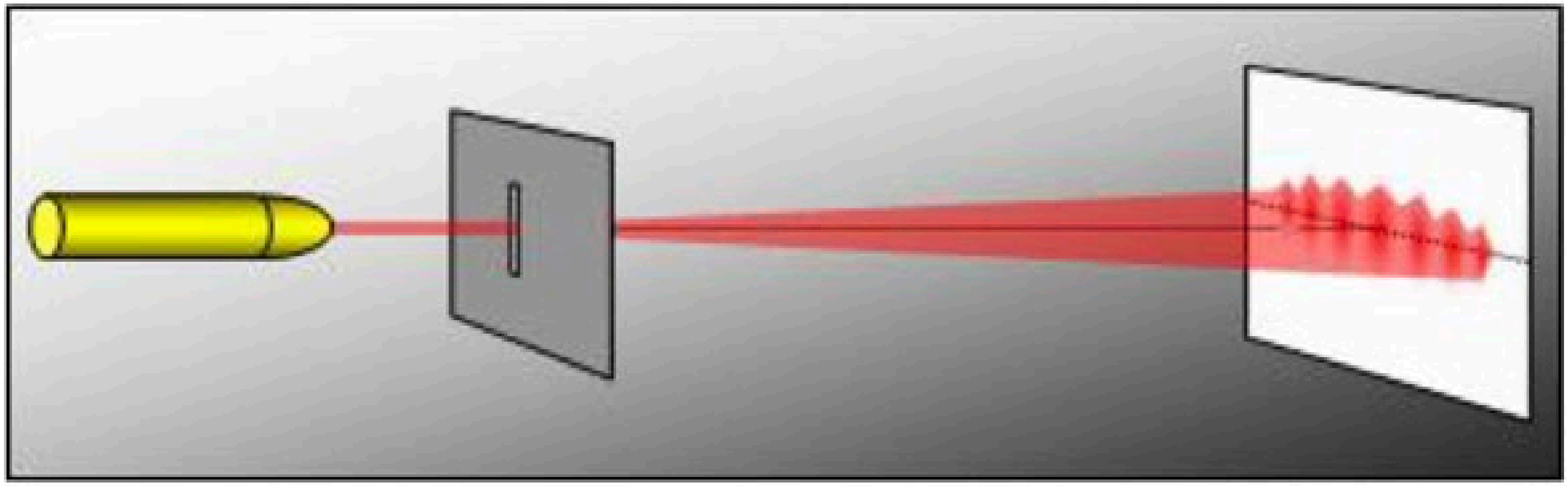
Slide 11 | Interference In a Ripple Tank



Images obtained from a ripple tank with a low level of water, in which the waves are generated simultaneously from two points that enter into contact with the water.

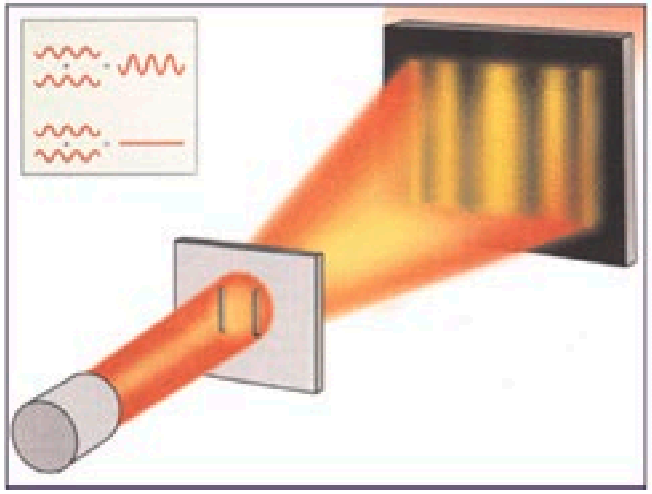
Credit: http://www.aoc.nrao.edu/~myun/bob/tutorial.html

1



Light from the laser beam
passes through a slit and
produces a diffraction pattern.

2



Young’s Experiment:
Light from the laser beam passes
through two narrow parallel slits,
producing an interference pattern.

Slide 12 | Light Interference

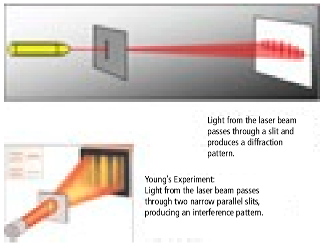
The laser beam passes through a narrow slit, generating a diffraction pattern.

The same beam passes through two very thin, close slits. The beam interferes in the same way as the waves in the ripple tank.

Credit:

http://www.educarchile.cl/ech/pro/app/detalle?ID=133072

http://www.nobelprize.org/nobel_prizes/themes/physics/ekspong/



Light from the laser beam passes through a slit and produces a diffraction pattern.

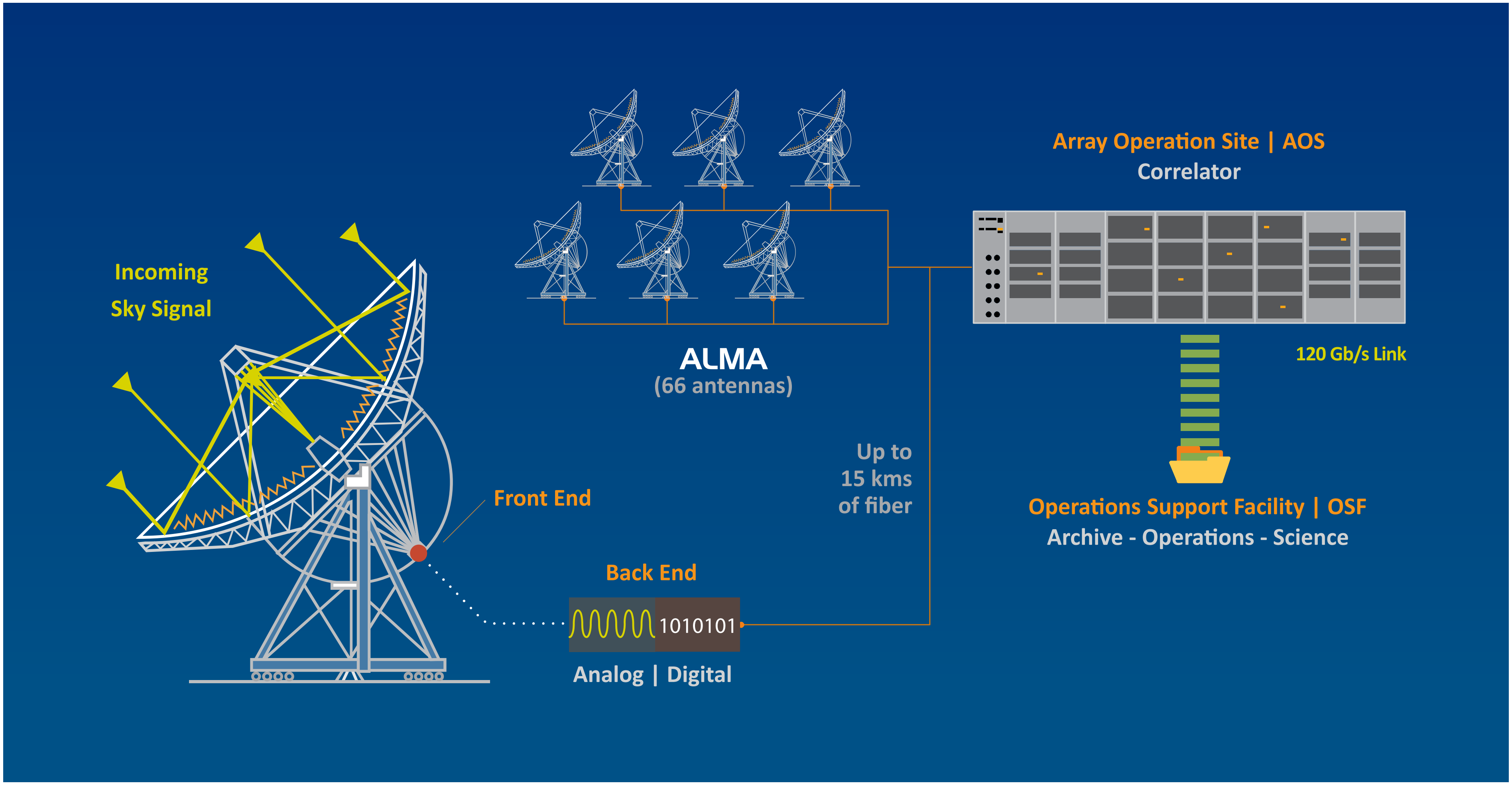
Young's Experiment:
Light from the laser beam passes through two narrow parallel slits, producing an interference pattern.


SCHEUERLE

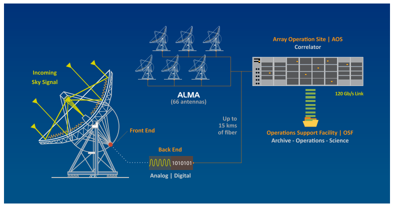
Slide 13 | Antenna Transporter

One of the two ALMA antenna transporters, Otto and Lore. They are 20 meters long, 10 meters wide and 6 meters tall. Each one has 28 wheels.

Credit: ALMA (ESO/NAOJ/NRAO).

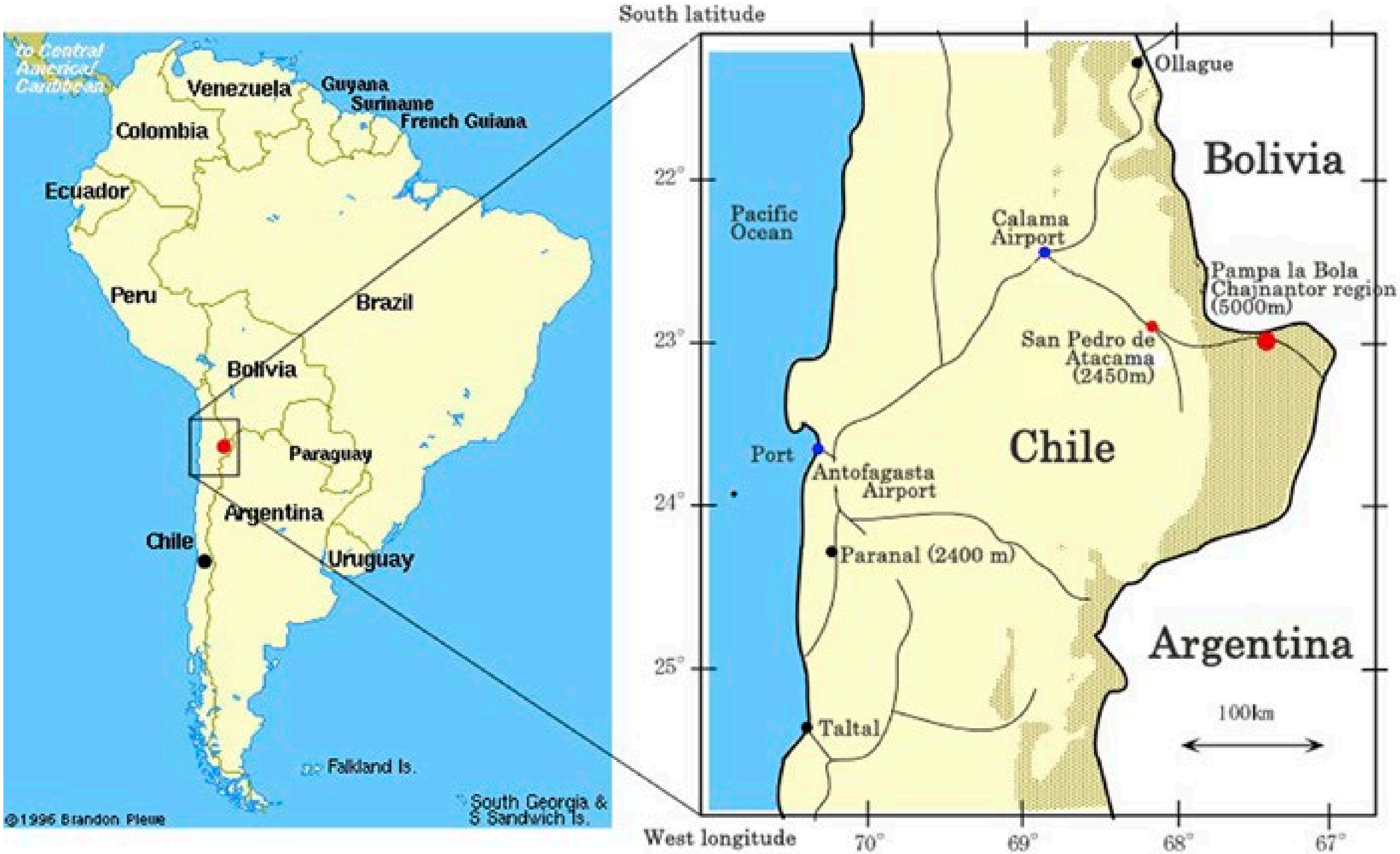

Incoming
Sky Signal
Front End
Back End
1010101
Analog | Digital
ALMA
(66 antennas)
Up to
15 kms
of fiber
Array Operation Site | AOS
Correlator
120 Gb/s Link
Operations Support Facility | OSF
Archive - Operations - Science

Slide 14 | How Does ALMA Work?

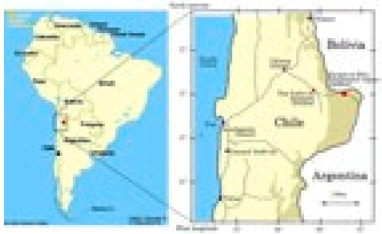


The ALMA Front End system is the first element in a complex chain of signal reception, conversion, processing and recording. The information is then carried to the Back End, where it is digitalized and processed in the Correlator, generating the information used by astronomers.

Credit: ALMA (ESO/NAOJ/NRAO).

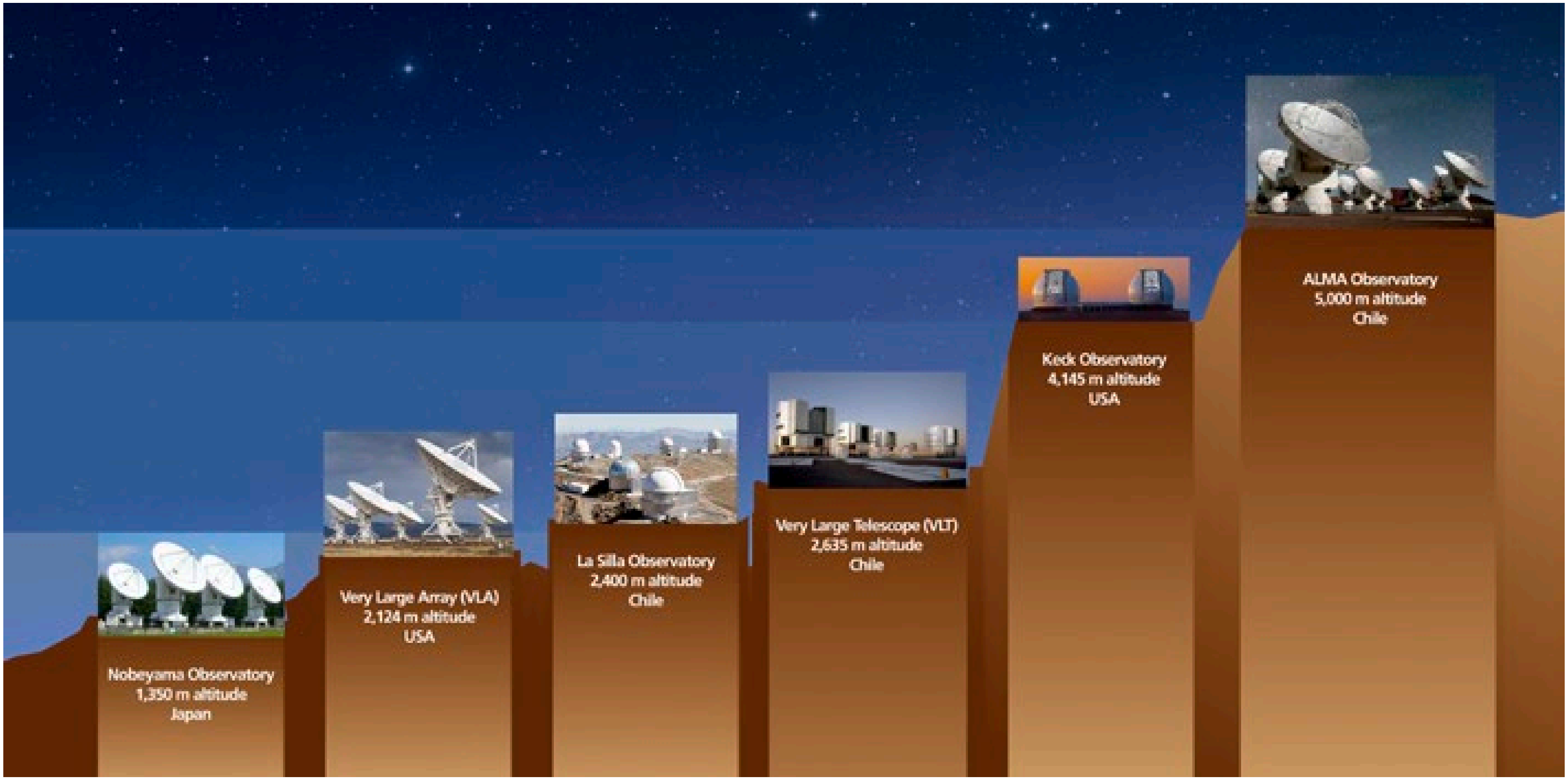

to Central America/ Caribbean
Venezuela
Guyana
Suriname
French Guiana
Colombia
Ecuador
Peru
Brazil
Bolivia
Paraguay
Argentina
Chile
Uruguay
Falkland Is.
South Georgia & S Sandwich Is.
©1996 Brandon Plewe
South latitude
West longitude
22°
23°
24°
25°
70°
69°
68°
67°
Ollague
Bolivia
Pacific Ocean
Calama Airport
Pampa la Bola
Chajnantor region
(5000m)
San Pedro de Atacama (2450m)
Port
Chile
Antofagasta Airport
Paranal (2400 m)
Argentina
100km
Taltal

Slide 15 | Geographic Location

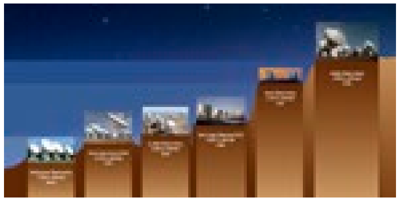


ALMA site on the Chajnantor Plateau, Antofagasta Region, Chile.

Credit: ALMA (ESO/NAOJ/NRAO).


Nobeyama Observatory
1,350 m altitude
Japan
Very Large Array (VLA)
2,124 m altitude
USA
La Silla Observatory
2,400 m altitude
Chile
Very Large Telescope (VLT)
2,635 m altitude
Chile
Keck Observatory
4,145 m altitude
USA
ALMA Observatory
5,000 m altitude
Chile

Slide 16 | Observatories



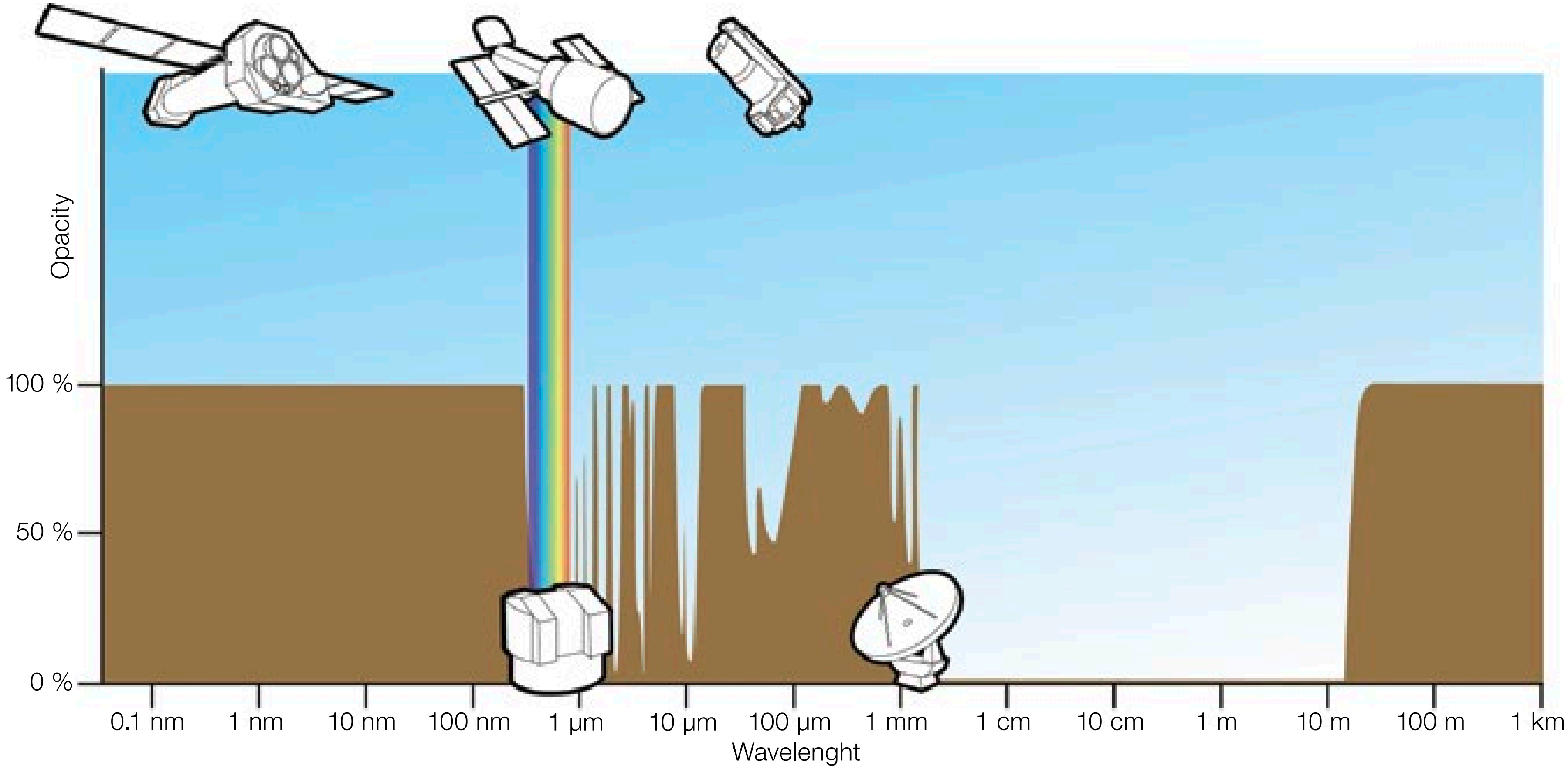
Comparison of altitudes at the locations of different observatories.

Credit: ALMA (ESO/NAOJ/NRAO)

Slide 17 | OSF

The ALMA Operations Support Facility (OSF) at an altitude of 2,900 m.

Credit: ALMA (ESO/NAOJ/NRAO), W. Garnier. Acknowledgments: General Dynamics C4 Systems.


Opacity
100 %
50 %
0 %
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelenght

Slide 18 | Atmospheric Opacity

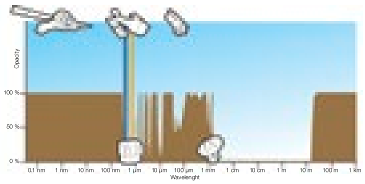
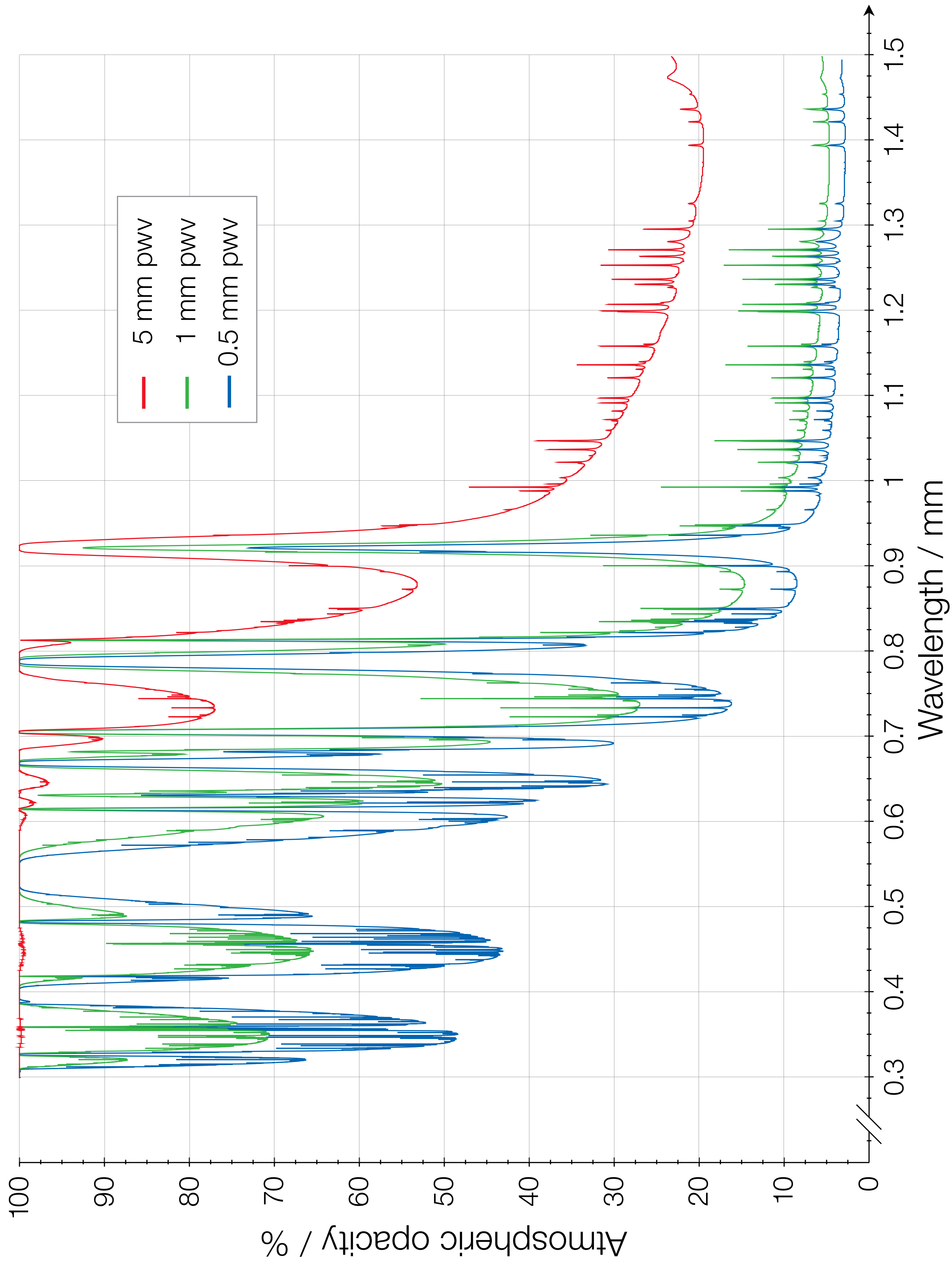
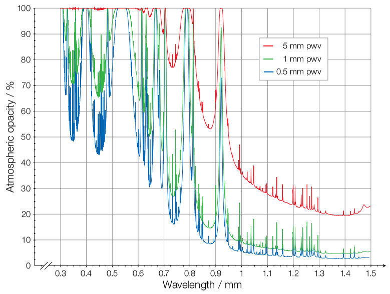


Illustration and description of atmospheric opacity. In this illustration, the level of the brown curve represents the opacity of the atmosphere at a given wavelength. The largest windows are found at visible wavelengths (marked by a rainbow) and at radio wavelengths from approximately 1 mm to 10 m. ALMA operates in an extreme region where opacity depends heavily on the altitude and aridity of the place.

Credit: ESA/Hubble (F. Granato).

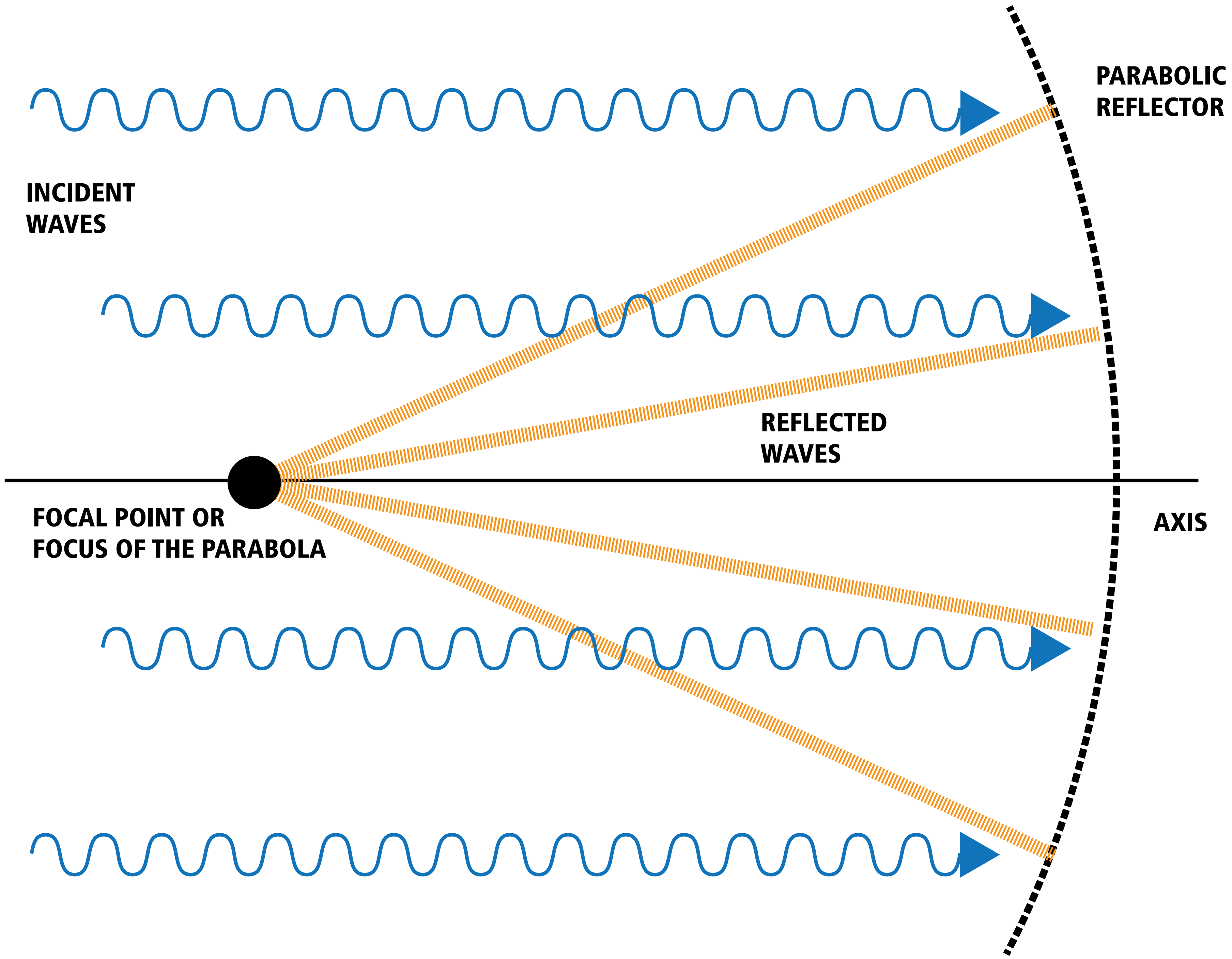

Atmospheric opacity / %
Wavelength / mm
5 mm pwv
1 mm pwv
0.5 mm pwv
0
10
20
30
40
50
60
70
80
90
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5

Slide 19 | Wavelength Regions



This illustration provides a closer view of the region of millimeter and sub-millimeter wavelengths, with the different lines showing how opacity depends heavily on the amount of precipitable water vapor (PWV) in the air.

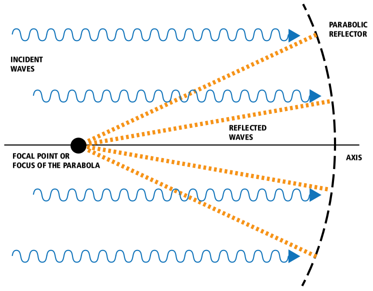
Credit: ESO/APEX.


PARABOLIC
REFLECTOR
INCIDENT
WAVES
REFLECTED
WAVES
FOCAL POINT OR
FOCUS OF THE PARABOLA
AXIS

Slide 20 | Parabola

An image of a parabolic reflector hit by parallel waves that are concentrated on the focal point.

Credit: ALMA(ESO/NAOJ/NRAO).



High and dry, the Chajnantor Plateau. Credit: ESO/Sergio Otarola

The Atacama Large Millimeter/sub-millimeter Array (ALMA), an international partnership of Europe, North America and East Asia in cooperation with the Republic of Chile, is the largest astronomical project in existence. ALMA is a single telescope of revolutionary design, composed of 66 high precision antennas located on the Chajnantor Plateau at an altitude of 5,000 meters in northern Chile.