In Search of our Cosmic Origins

Educational Material for ALMA

The Atacama Large Millimeter/submillimeter Array

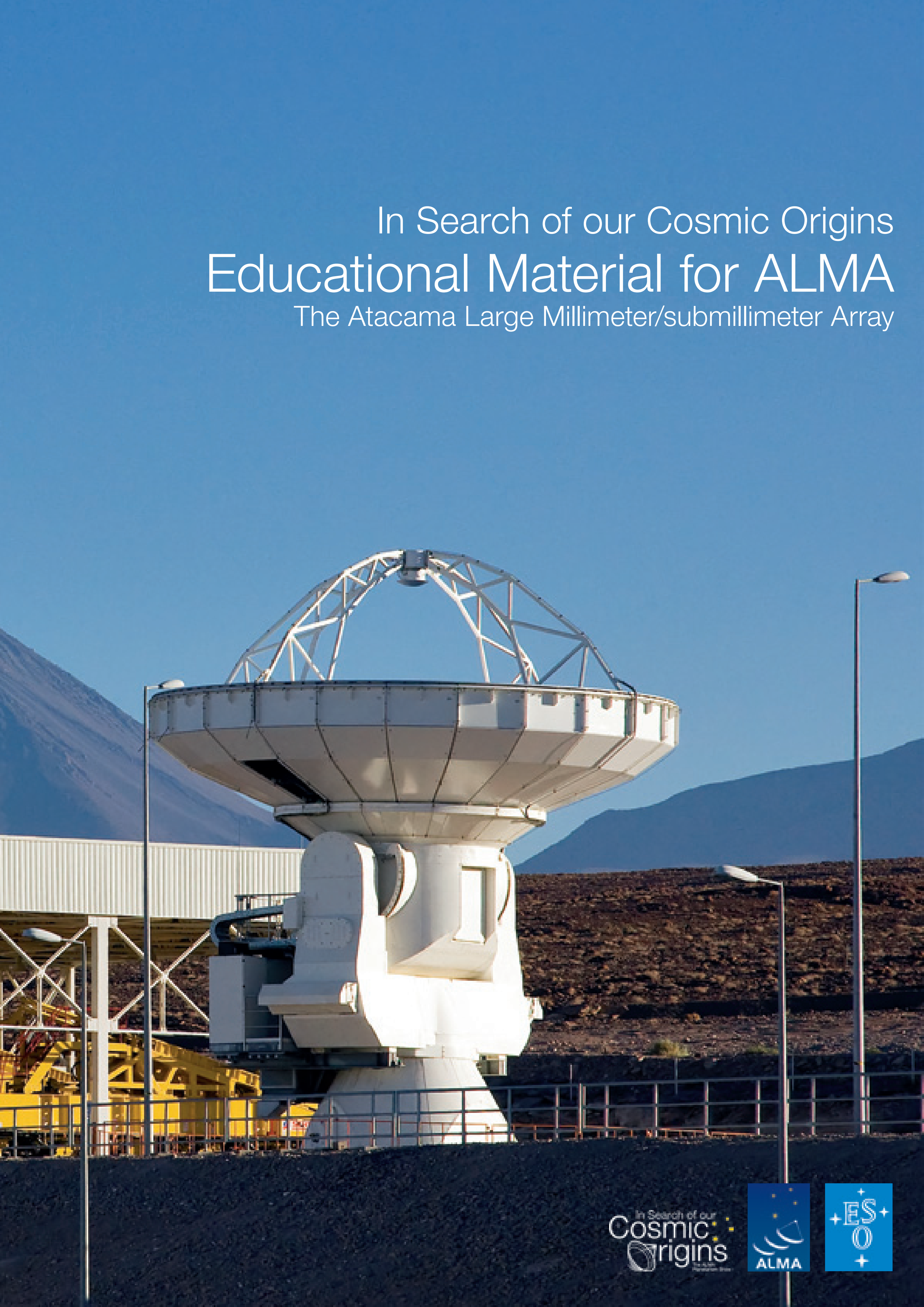

Table of Contents

Cover image
One of the Atacama Large Millimeter/submillimeter Array (ALMA) antennas in front of the Transporter Shelter at the Operation Support Facility in the Chilean Andes, 2900 m above sea level. Licancabur volcano is visible in the background. Credit: Iztok Bončina/ALMA (ESO/NAOJ/NRAO)

These education sheets are available online with solutions at: www.cosmicorigins.org/education.php
"In Search of our Cosmic Origins" is a popular scientific planetarium show about the ALMA project, appealing to a wide audience: www.cosmicorigins.org
Find out more about ALMA at: www.eso.org/alma and www.almaobservatory.org

2nd edition, April 2010

What is ALMA?

High on the Chajnantor plateau in the Chilean Andes, the European Southern Observatory (ESO), together with its international partners, is building the Atacama Large Millimeter/submillimeter Array, ALMA — a state-of-the-art telescope to study light from some of the coldest objects in the Universe. This light has a typical wavelength of around a millimetre, lying between infrared light and radio waves in the electromagnetic spectrum, and is therefore known as millimetre and submillimetre radiation.

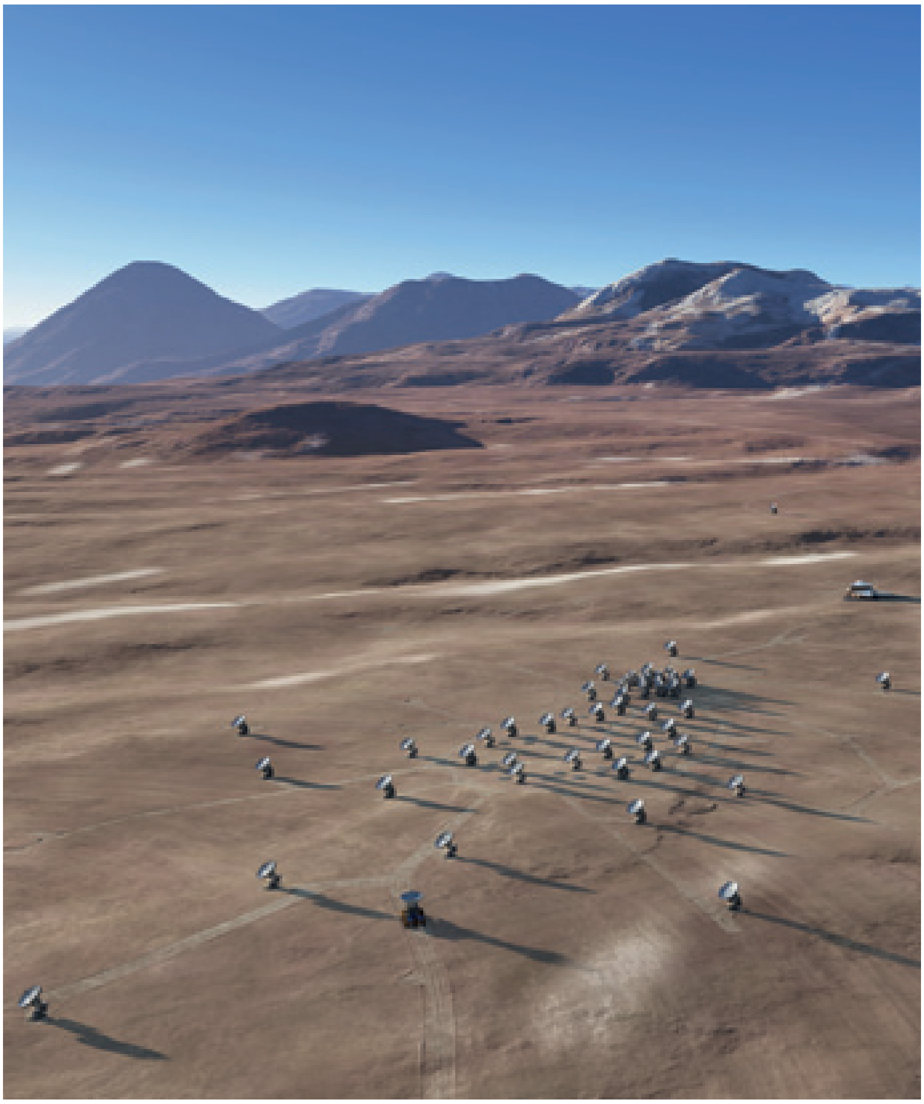

Figure 1.1
The Atacama Large Millimeter/submillimeter Array (ALMA) is the largest astronomical project in existence. It is a revolutionary astronomical telescope, comprising an array of 66 giant 12-metre and 7-metre diameter antennas observing at millimetre and submillimetre wavelengths. It is being built on the breathtaking location of the Chajnantor plateau, at 5000 metres altitude in the Chilean Andes, and will start scientific observations in 2011.
Credit: ALMA (ESO/NAOJ NRAO)/L. Calçada

What is submillimetre astronomy?

Light at these wavelengths comes from vast cold clouds in interstellar space, at temperatures only a few tens of degrees above absolute zero, and from some of the earliest and most distant galaxies in the Universe. Astronomers can use it to study the chemical and physical conditions in molecular clouds — the dense regions of gas and dust where new stars are being born. Often these regions of the Universe are obscured and therefore dark in visible light, but they shine brightly in the millimetre and submillimetre part of the spectrum.

Figure 1.2
Crushed water bottles illustrate the low atmospheric pressures at high altitude and the difference in pressure between the ALMA Array Operations Site and the Operations Support Facility. The empty bottles were sealed at the 5000 m Array Operations Site and brought down to the 2900 m Operations Support Facility, where the relatively higher pressure crushed them.
Credit: ALMA (ESO/NAOJ/NRAO)

Why build ALMA in the high Andes?

Millimetre and submillimetre radiation opens a window into the enigmatic cold Universe, but the signals from space are heavily absorbed by water vapour in the Earth's atmosphere. Telescopes for this kind of astronomy must be built on high, dry sites, such as the 5000 m high plateau at Chajnantor, one of the very highest astronomical observatory sites on Earth.

Here ESO is building ALMA, the largest astronomical project in existence. The ALMA site, some 50 km east of San Pedro de Atacama in northern Chile, is in one of the driest places on Earth. Astronomers find unsurpassed conditions for observing, but they must operate a frontier observatory under very difficult conditions. Chajnantor is more than 750 m higher than the observatories on Mauna Kea, and 2400 m higher than the VLT on Cerro Paranal.

Figure 1.3
Working conditions at 5000 m altitude are difficult. Workers constructing ALMA at the high Chajnantor Array Operations Site.
Credit: ALMA (ESO/NAOJ/NRAO)

Why is ALMA an interferometer?

ALMA will be a single telescope of revolutionary design, composed initially of 66 high precision antennas, and operating at wavelengths of 0.3 to 9.6 mm. Its main 12-metre array will have fifty antennas, 12 metres in diameter, acting together as a single telescope — an interferometer. An additional compact array of four 12-metre and twelve 7-metre antennas will complement this. The antennas can be spread across the desert plateau over distances from 150 m to 16 km, which will give ALMA a powerful variable "zoom". It will be able to probe the Universe at millimetre and submillimetre wavelengths with unprecedented sensitivity and resolution, with a vision up to ten times sharper than the Hubble Space Telescope, and complementing images made with the VLT interferometer (VLTI).

ALMA — in search of our cosmic origins

ALMA is the most powerful telescope for observing the cool Universe — molecular gas and dust as well as the relic radiation of the Big Bang. ALMA will study the building blocks of stars, planetary systems, galaxies, and life itself. By providing scientists with detailed images of stars and planets being born in gas clouds near our Solar System, and detecting distant galaxies forming at the edge of the observable Universe, which we see as they were roughly ten billion years ago, it will let astronomers address some of the deepest questions of our cosmic origins.

ALMA's construction will be completed around 2012, but early scientific observations with a partial array will begin around 2011.

The ALMA Project is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile.

Figure 1.4
An artist's rendering of how ALMA will look. Computer-generated models of the antennas are shown superimposed on a photograph of the Chajnantor site.
Credit: ALMA (ESO/NAOJ/NRAO) /L. Calçada/H. Heyer/H. Zodet

Figure 1.5
Colour composite image of Centaurus A, revealing the lobes and jets emanating from the active galaxy's central black hole. This is a composite of images obtained with three instruments, operating at very different wavelengths. The 870 µm submillimetre data, from LABOCA on APEX, are shown in orange. X-ray data from the Chandra X-ray Observatory are shown in blue. Visible light data from the Wide Field Imager (WFI) on the MPG/ESO 2.2-metre telescope located at La Silla, Chile, show the background stars and the galaxy's characteristic dust lane in close to "true colour".
Credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R. Kraft et al. (X-ray)

About ESO

ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe and the world's most productive astronomical observatory. It is supported by 14 countries: Austria, Belgium, the Czech Republic, Denmark, France, Finland, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, Switzerland and the United Kingdom. ESO carries out an ambitious programme focused on the design, construction and operation of powerful ground-based observing facilities enabling astronomers to make important scientific discoveries. ESO also plays a leading role in promoting and organising cooperation in astronomical research. ESO operates three unique world-class observing sites in Chile: La Silla, Paranal and Chajnantor. At Paranal, ESO operates the Very Large Telescope, the world's most advanced visible-light astronomical observatory and VISTA, the world's largest survey telescope. ESO is the European partner of a revolutionary astronomical telescope ALMA, the largest astronomical project in existence. ESO is currently planning a 42-metre European Extremely Large optical/near-infrared Telescope, the E-ELT, which will become "the world's biggest eye on the sky".

Find out more on the web
www.eso.org/alma
www.almaobservatory.org/

What is submillimetre astronomy?

The electromagnetic spectrum

The visible light that can be seen with the human eye is just a small part of the whole spectrum of electromagnetic radiation. The full electromagnetic spectrum runs from low frequency radio waves at the long wavelength end to gamma rays at the high frequency, short wavelength end.

Astronomers use all parts of the electromagnetic spectrum to study the Universe, as electromagnetic radiation at different wavelengths tells us about different physical processes. Each set of observations gives a different piece of the puzzle.

Figure 2.1
Colour composite image showing the combination of different wavelengths used to study a single astronomical target. Here, an expanding bubble of ionised gas about ten light-years across is causing the surrounding material to collapse into dense clumps where new stars are then formed. The red glow comes from ionised hydrogen gas emitting characteristic H-alpha emission (caused by transitions in the Balmer series between $n = 3$ to $n = 2$, i.e. Balmer-alpha), while the blue clouds show submillimetre wavelength emission from cosmic dust. The H-alpha emission really does have a visible red colour, while the submillimetre emission — shown here in blue — is actually at a wavelength invisible to the human eye.
Credit: ESO/APEX/DSS2/SuperCosmos/Deharveng(LAM)/Zavagno(LAM)

Millimetre and submillimetre waves have a wavelength, as the name suggests, of about one millimetre. This places them between infrared light and radio waves in the electromagnetic spectrum. The wavelength λ and frequency f of light are related by

$$c = f\,\lambda$$

where c is the speed of light.

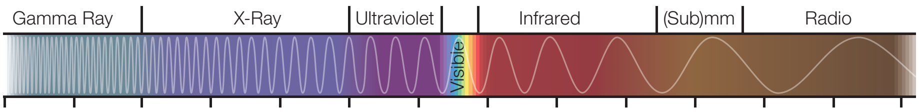

Figure 2.2
The electromagnetic spectrum: this diagram shows the electromagnetic spectrum, from high frequency, short wavelength gamma rays, to low frequency, long wavelength radio waves. Visible light forms just a small part of the full spectrum. The millimetre and submillimetre-wavelength range where ALMA operates is marked (sub)mm. Credit: Robert Hurt/ESO

What is the frequency of light with a wavelength of 1 millimetre?

These wavelengths are particularly important for exploring the "cold Universe", in other words, some of the coldest objects in the cosmos.

Blackbody radiation

One way to examine this is to consider blackbody radiation. Blackbody radiation is the heat radiation emitted by an idealised object, called a blackbody, which absorbs all radiation that falls onto it before re-emitting it. Blackbody radiation has a characteristic spectrum, which depends only on the object's temperature. Many astronomical objects radiate with a spectrum that approximates a blackbody spectrum at a given temperature.

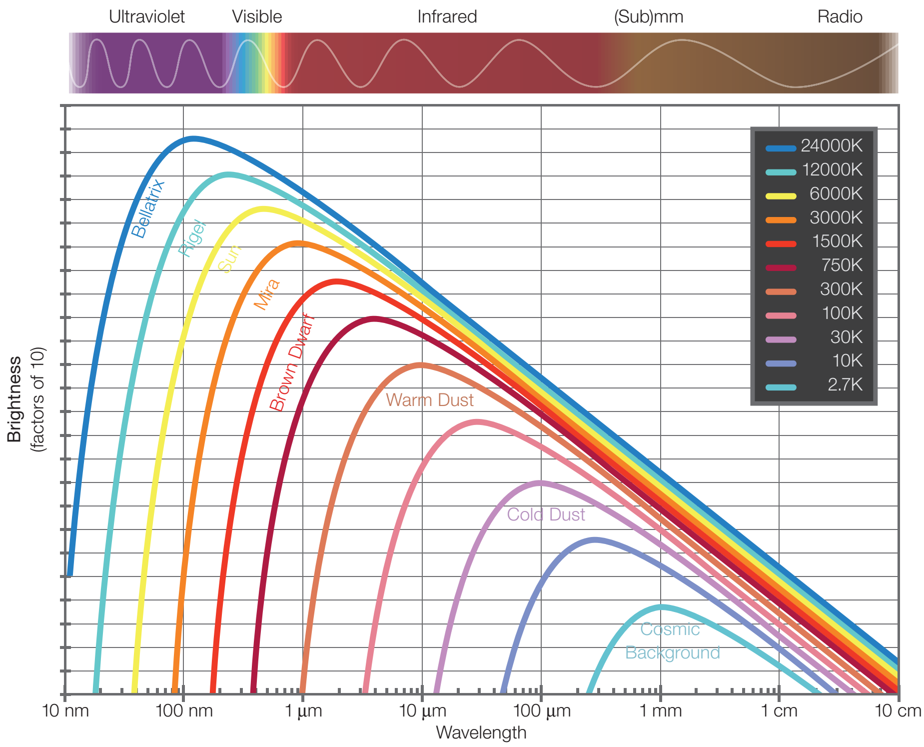

Figure 2.3
Blackbody radiation curves as a function of temperature: In this graph, each curve shows the characteristic blackbody radiation spectrum associated with a certain temperature. Note how the curves change as the temperature increases or decreases. Credit: Robert Hurt/ESO

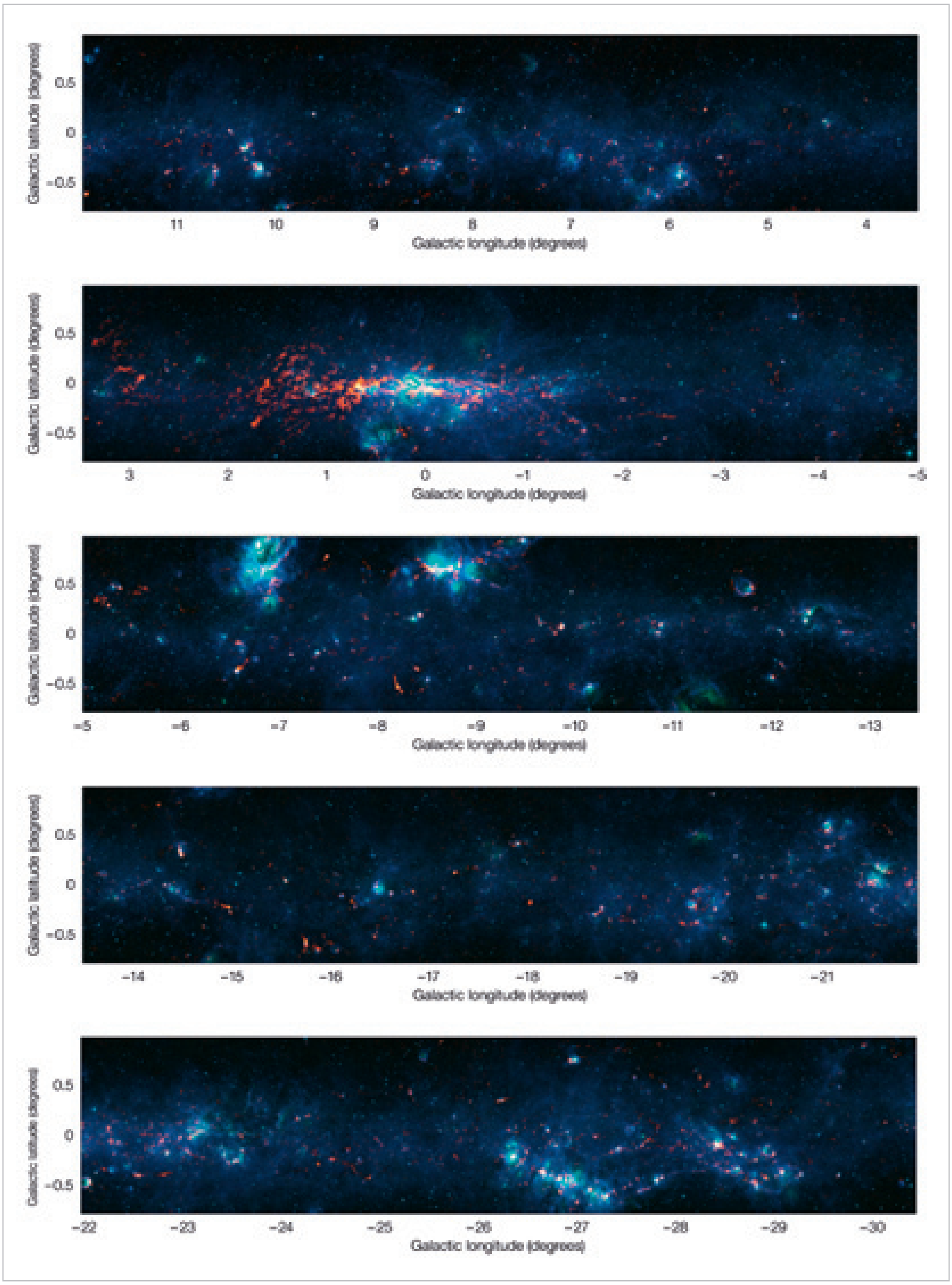

Figure 2.4

Colour-composite image of part of the Galactic Plane, as seen in submillimetre wavelengths by the ATLASGAL survey, divided into sections. In this image, which includes the centre of our Galaxy, the submillimetre-wavelength data are shown in red, overlaid on a view of the region in infrared light, from the Midcourse Space Experiment (MSX) in green and blue. The total size of the image is approximately 42 degrees by 1.75 degrees.

Credit: ESO/APEX & MSX/IPAC/NASA

The relationship between temperature and wavelength

As the temperature of the blackbody increases, the peak in its emission spectrum shifts. This is why a piece of metal starts to glow red hot (predominantly red wavelengths), and then white hot (wavelengths in the middle of the visible range), as it is progressively heated.

The peak wavelength λ_{max} of the blackbody distribution, as a function of temperature *T*, is given by Wien's displacement law:

$$\lambda_{max} = \frac{b}{T} \qquad (b = 2.897769 \times 10^{-3}\ \mathrm{m{\cdot}K})$$

where *b* is known as Wien's displacement constant.

Look at the form of the equation. How does λ_{max} vary with temperature? How will the peak wavelength change as the temperature increases?

We can use Wien's displacement law to calculate the peak wavelength of blackbody emission from objects at different temperatures. Complete the blank cells in the table below.

Object	Typical temperature	Peak wavelength
A star like our Sun (surface temperature)	5500 K	
Room temperature (approximately)	300 K	
Cold dust clouds in interstellar space		0.15 mm

Notice how the peak wavelength for emission from the Sun is in the visible light range for the human eye. Is this a coincidence?

Notice how, as the temperature of the object we wish to study drops to a few tens of Kelvin, the peak wavelength is around the submillimetre/millimetre range. Some of the coldest objects in the Universe, such as the giant clouds of molecular gas and dust in which new stars are formed, have temperatures in this range. This is why submillimetre astronomy is vital, to study the peak wavelengths at which these clouds emit most of their heat radiation.

Why build ALMA in the high Andes?

ALMA is being constructed on the high plateau of Chajnantor, in the Chilean Andes, at an altitude of 5000 m. Here, in the arid Atacama region, we can find the necessary high and dry conditions for doing submillimetre astronomy.

Seeing through the atmosphere

The ability of electromagnetic radiation to pass through Earth's atmosphere depends greatly on its wavelength. We measure this in terms of the atmospheric transparency or opacity (opaqueness). Opacity of 100% corresponds to transparency of 0%, and vice versa. Figure 3.1 shows how the opacity of the atmosphere varies with wavelength. At 100% opacity, the radiation is completely blocked, while at 0% opacity it is completely transmitted.

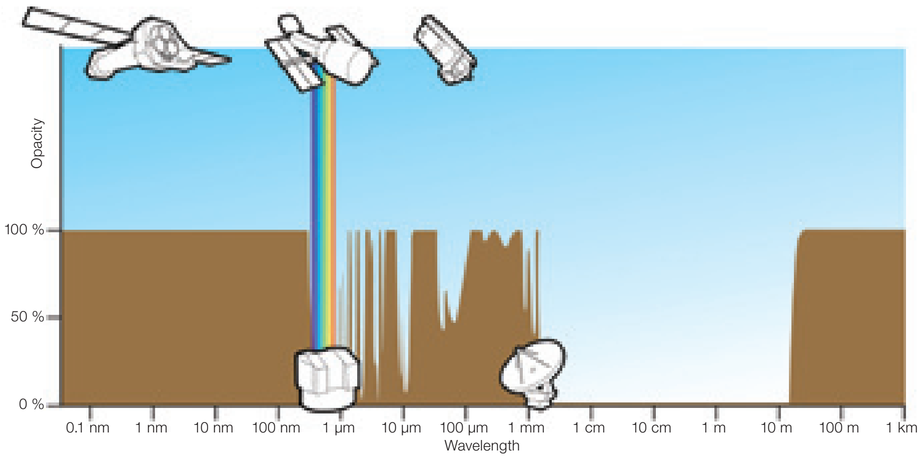

Figure 3.1
Atmospheric opacity graph and description: In this graph, the level of the brown curve represents how opaque the atmosphere is at the given wavelength. The major windows are at visible wavelengths (marked by the rainbow) and at radio wavelengths from about 1 mm to 10 m. ALMA operates in a borderline region, where the opacity depends strongly on how high and dry the site is.
Credit: ESA/Hubble (F. Granato)

The atmosphere absorbs the faint signals from space that astronomers want to collect with ALMA, and also emits radiation of its own. The main factor at ALMA's wavelengths is water vapour in the air. This is why a high, dry site is so important.

The amount of water vapour is usually measured in millimetres of "precipitable water vapour" (pwv). This is the depth of the puddle that would be formed if all the water above the site were to fall as rain. The average value over the whole planet is about 2.5 cm, but for submillimetre astronomy we need extremely dry conditions. At Chajnantor, during the period from April to December, the median amount of water vapour is about 1 mm, and it can fall below 0.5 mm in particularly dry conditions!

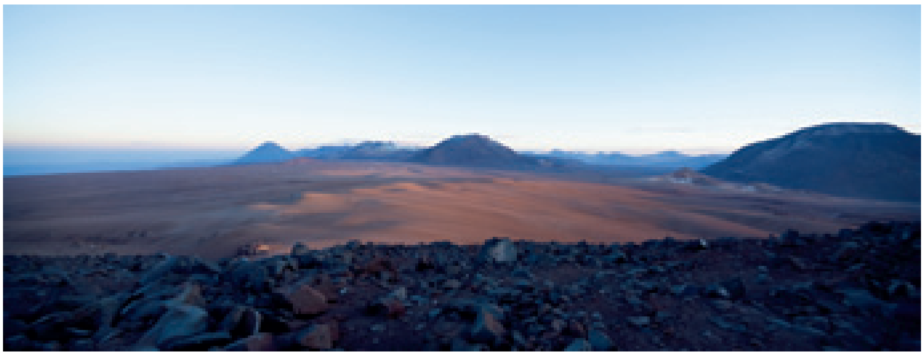

Figure 3.2
The Chajnantor plateau at sunrise. ALMA is being built on this remote 5000 m altitude site.
Credit ALMA (ESO/NAOJ/NRAO)

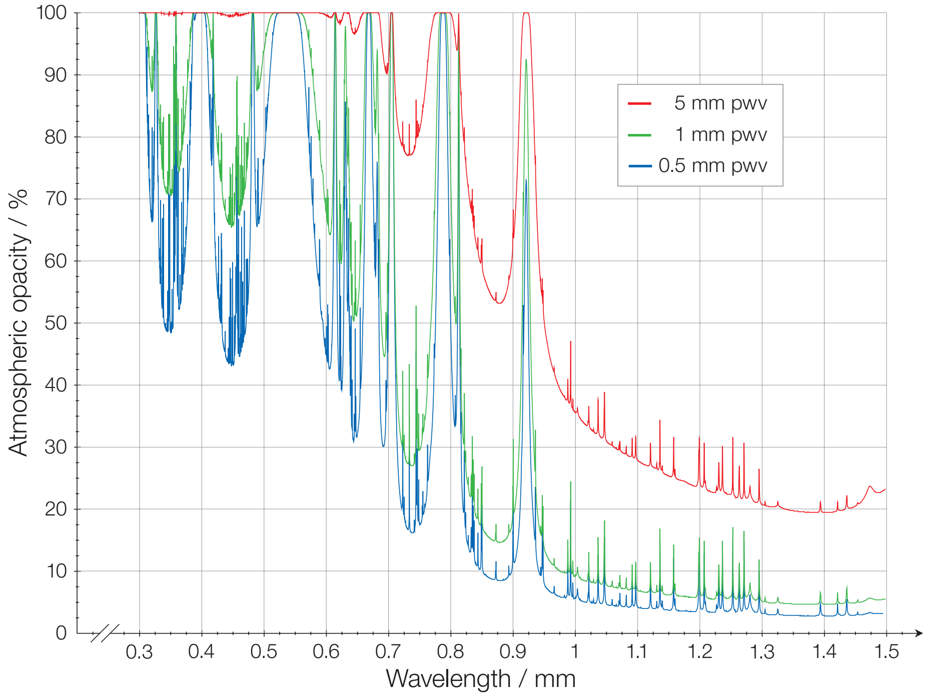

Figure 3.3

This graph shows a closer view of the millimetre and submillimetre wavelength region, with the different lines showing how the opacity depends strongly on the amount of precipitable water vapour (pwv) in the air.
Credit: ESO/APEX

Look at the graph above, which shows a more detailed view of the opacity of the atmosphere at millimetre and submillimetre wavelengths. The different curves show the opacity for different levels of precipitable water vapour in the atmosphere (5 mm, 1 mm, and 0.5 mm for red, green, and blue respectively). How does the opacity change as the amount of water vapour increases?

How does the opacity change, broadly speaking, as the wavelength becomes shorter?

At the longer wavelengths, such as 1.2 mm, how critical is it to have the lowest levels of water vapour? You may find it helpful to compare what percentage of light is transmitted (take 100% minus the percentage opacity), at 5 mm pwv and 0.5 mm pwv. What about at shorter wavelengths, such as 0.35 mm?

Working at high altitude

ALMA itself is being built at the Array Operations Site, at an altitude of 5000 m on the Chajnantor plateau. The conditions there may be excellent for submillimetre astronomy, but they are very harsh for living and working. This is why the everyday operations of the observatory will be handled from a lower site, the Operations Support Facility, at an altitude of 2900 m.

Figure 3.4
The ALMA Operations Support Facility at an altitude of 2900 m. Credit: H. Sommer/ALMA (ESO/NAOJ/NRAO)

At high altitudes, the atmospheric pressure is lower compared to sea level, and the amount of oxygen available is correspondingly lower. In this exercise, we will examine how the atmospheric pressure at ALMA compares to sea level, and other high altitude sites.

Atmospheric pressure with altitude – the isothermal atmosphere

We can make a simple model of the way that atmospheric pressure decreases with altitude by assuming that the pressure falls exponentially with increasing height. This model is described as "isothermal" because we assume that the temperature of the air remains constant. This is not perfectly accurate, but it is a reasonable approximation. In other words

$$p(h) = p_0 e^{-(h/H)}$$

where p is the pressure as a function of the height h above sea level. There are two constants in the equation: p_0 is the pressure at sea level (where $h = 0$) and H is the height at which the pressure has dropped by a factor of 1/e. This characteristic height is known as the "scale height" of the atmosphere.

Using a fixed scale height of 8400 m

The pressure at sea level (altitude 0 m) is about 100 kPa, and the scale height of the atmosphere is approximately 8400 m (this can be derived using a basic model of the gas in the atmosphere).

Use this information to estimate the atmospheric pressure at the ALMA Operations Support Facility (2900 m), the ALMA Array Operations Site (5000 m), and at the summit of Everest (8848 m), and complete the **blue** *column in the table below.*

Calculating the scale height, using the measured pressure on Everest

In fact, the pressure on the summit of Mount Everest is measured as about 33 kPa.

Use this information, and the equation above, to get another estimate of the scale height H of the atmosphere.

Use this information to estimate the atmospheric pressures at the altitudes of the ALMA OSF and AOS, and complete the **orange** *column in the table below.*

Location	Altitude	Atmospheric pressure (scale height 8.4 km)	Atmospheric pressure (scale height calculated from Everest pressure)	Atmospheric pressure (actual measured values)
Sea level	0 m	100 kPa	100 kPa	100 kPa
ALMA Operations Support Facility	2900 m			75 kPa
ALMA Array Operations Site, Chajnantor	5000 m			55 kPa
Mount Everest summit	8848 m		33 kPa	33 kPa

Note that, at the altitude of the ALMA Array Operations Site on Cerro Chajnantor, the pressure is approximately half that at sea level. This also means that only half as much oxygen is available as at sea level. At these very high altitudes, there is the risk of altitude-related illnesses and even death.

This is why people working at ALMA only go to the Array Operations Site when it is absolutely necessary. Normally, they will remain at the lower Operations Support Facility, where the atmospheric pressure is higher.

Why is ALMA an interferometer?

ALMA will comprise an array of 66 giant 12-metre and 7-metre diameter antennas, observing at millimetre and submillimetre wavelengths. The signals from the individual antennas will be combined in what is known as an "interferometer", so that ALMA will act like a single, giant telescope. In this exercise, we will investigate the effect of a telescope's size on its resolving power, and discover why it is so important that ALMA is built as a giant interferometer.

Telescope angular resolution and the diffraction limit

The diameter of a telescope determines its resolving power, or the level of fine detail that it can detect (the sharpness of its images). Light passing through an aperture, passing through a lens, or being reflected by a mirror, spreads out due to diffraction. This spreading out creates a fundamental limit on the finest details (smallest angles) that can be resolved by the telescope.

For a telescope with a primary mirror of diameter D, operating at a wavelength λ, the maximum resolution of the telescope (expressed as an angle in radians) is approximately given by

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

How does the resolution of a telescope change as the wavelength increases? Does it improve, or get worse? What about when the size of the telescope increases?

Radians, degrees, arcminutes and arcseconds

In the equation above, the angle θ must be measured in radians, rather than degrees. There are 2π radians in a circle, as opposed to 360 degrees. Therefore, to convert from radians to degrees, multiply by $360/2\pi$.

Astronomers often measure angles smaller than a degree in either arcminutes or arcseconds. You may also see the terms "minutes of arc" or "seconds of arc". There are 60 arcminutes in a degree, and 60 arcseconds in an arcminute (i.e. 3600 arcseconds in a degree).

Converting between angles and distances

This finest angle θ tells us roughly the smallest feature that can be seen at a given distance. For small angles θ, we can convert the angle into a size at a given distance with the equation

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

where θ is the angle subtended by an arc of length x at a distance r. Remember that the angle must be expressed in radians.

Figure 4.1
One of Galileo's original telescopes, disassembled to show the separate housings for the objective and eyepiece lenses. Credit: Istituto e Museo di Storia della Scienza, Florence

The distance from Earth to the Moon is approximately 380 000 km, and the Moon's diameter is about 3500 km. What is its angular size in the sky in arcminutes?

Comparison of resolutions at visible light wavelengths

Use the equation above to calculate the diffraction limits for some modern optical telescopes, as well as for the human eye and for Galileo's original telescopes. Use a wavelength for visible light of 500 nm. Complete the table below. Express your results in arcseconds.

Description	Wavelength	Diameter	Diffraction-limited angular resolution
Human eye	500 nm	5 mm	
Galileo's 1609 telescope	500 nm	1.5 cm	
Hubble Space Telescope	500 nm	2.4 m	
ESO Very Large Telescope (one of its four 8.2-metre telescopes)	500 nm	8.2 m	

Note that these values are theoretical upper limits. In the case of the human eye, imperfections in the eye limit the effective resolution to about 1 arcminute (60 arcseconds). Imperfections in the optics of telescopes can also reduce the effective resolution. Furthermore, turbulence in the Earth's atmosphere can also give an effective resolution worse than the diffraction limit. At visible light wavelengths, the atmospheric turbulence limits the resolution to about 1 arcsecond. This is one of the principal reasons why the Hubble Space Telescope was put into space, to allow it to observe at the diffraction limit, clear of Earth's atmosphere.

Advanced technology such as "adaptive optics" can also be used to remove or reduce the effect of atmospheric turbulence, allowing ground-based telescopes to make images as sharp as though they were above the atmosphere, in space.

Figure 4.2
ALMA's antennas will be moved across the desert plateau from position to position by custom transporter vehicles, in order to reconfigure the ALMA array. The 12-metre diameter antennas weigh over 100 tons, so the transporters must be powerful giants to be able to lift and move them. Each of the two transporter vehicles is 10 m wide, 20 m long and 6 m high, weighs 130 tons and has as much power as two Formula 1 engines.
Credit: ALMA (ESO/NAOJ/NRAO)

What were the finest details that Galileo could discern on the Moon using his telescope in 1609, assuming perfect optics? What about the Hubble Space Telescope? Use the numbers given above to calculate your answers.

Resolution at ALMA wavelengths

Now let's consider ALMA, which observes the Universe at wavelengths of about 1 mm, instead of visible light wavelengths of about 500 nm.

As the wavelength is increased, the resolution of a telescope of a given size will be worse at millimetre wavelengths than at visible wavelengths. Therefore, millimetre- and submillimetre-wavelength telescopes such as ALMA must, in general, be even larger than visible-light telescopes.

What angular resolution would the Hubble Space Telescope have if it observed at 1 mm wavelength?

Figure 4.3
The Atacama Pathfinder Experiment (APEX) telescope on Chajnantor. It has a single 12-metre diameter dish, and is based on a prototype ALMA antenna.
Credit: APEX (MPIfR/ESO/OSO)

Also on the Chajnantor plateau, with ALMA, is a single-dish telescope APEX, the Atacama Pathfinder Experiment. It has a 12-metre diameter dish, similar to a single ALMA antenna, to collect millimetre and submillimetre wavelengths. What is its angular resolution at 1 mm wavelength?

How big would a single-dish telescope like APEX have to be to match the Hubble Space Telescope's visible-light resolution, if APEX observes at a wavelength of 1 mm? Is this feasible?

Using interferometry for telescopes

Using a technique known as interferometry, multiple individual telescopes can be linked together and their signals combined, to simulate the effect of a single giant telescope with an aperture as large as the whole group. This technique is also known as aperture synthesis.

In this case, the effective resolution of the telescope is given by

$$\theta \approx \frac{\lambda}{B}$$

where *B* is now the maximum separation (or "baseline") between individual telescopes in the group. For ALMA, we refer to the individual dishes as "antennas", and the whole collection as the telescope. ALMA will have an array of 66 giant 12-metre and 7-metre diameter antennas, spread across the Chajnantor plateau over distances of up to 16 km.

A major advantage of interferometry is that one can simulate the effect of a single telescope which is much larger than we could actually build. It would be impossible to build a single 16-kilometre diameter antenna for making submillimetre observations, both in terms of engineering difficulty and cost!

If the ALMA antennas are spread over 16 km, what is ALMA's resolution when observing at a wavelength of 1 mm? How does this compare to the Hubble Space Telescope's resolution at visible wavelengths?

Figure 4.4
Artist rendering of the central regions of the ALMA Array, in its extended configuration.
Credit: ALMA (ESO/NAOJ/NRAO) /L. Calçada

Notes

www.eso.org/alma

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