It's FREEZING out there!

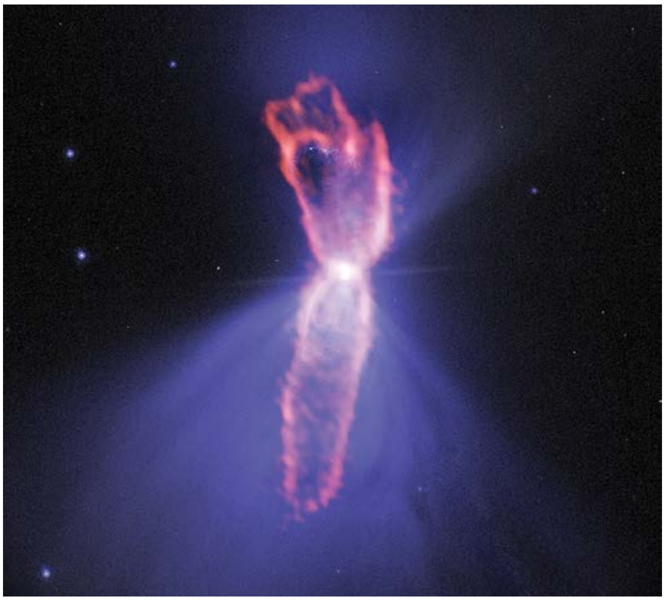
Our winters may bring some chilly mornings, but these are relatively warm compared to low temperatures that occur elsewhere. *Quest* takes a look at some of the coldest places.

Coldest place in the universe

The Boomerang Nebula, some 5 000 light years from Earth in the constellation Centaurus, is the coldest natural object in the universe found so far. Its temperature is approximately −272°C, just one degree above absolute zero, or zero kelvin (0 K). Even the temperature of outer space – more correctly, the Cosmic Microwave Background Radiation – is a slightly warmer 2.7 K.

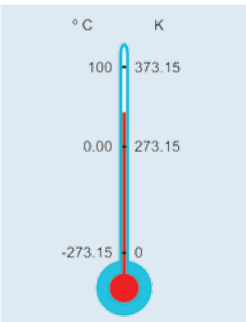
A nebula is a cloud of dust and gas ejected from a bright, central star towards the end of its life, when it has used up its nuclear fuel. The Boomerang Nebula is a so-called pre-planetary nebula, at a very early stage of this process. Its ultracold temperature was discovered by two astronomers in 1995, one of whom – Dr Raghvendra Sahai of NASA's Jet Propulsion Laboratory – had predicted the existence of such cold regions in a paper published five years previously.

The nebula was given its name a decade before that by two astronomers who observed it in 1980 using the 3.9 m Anglo-Australian Telescope in Australia. Unable to see it clearly, they noted a slight asymmetry in the nebula's lobes, which brought the shape of Australia's iconic boomerang to mind. But more detailed images captured in 1998 and 2005 by the Hubble Space Telescope, launched by the space shuttle Discovery in April 1990, revealed that the nebula had a bow-tie shape.



A composite image of the Boomerang Nebula, showing the hourglass-shaped outflow detected with ALMA observations (orange) on top of an image from the Hubble Space Telescope (blue). The hourglass outflow stretches more than three trillion kilometres from end to end, and is the result of a jet that is being fired by the central star.

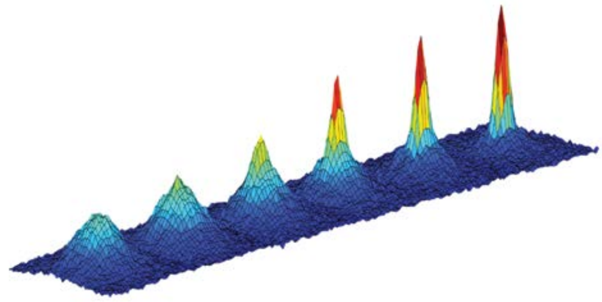
More recently, Sahai and co-workers using the Atacama Large Millimetre/submillimetre Array (ALMA), an international radio astronomy facility in Chile, released images in 2013 and 2017 that showed a much broader central disc and a more elongated outflow. The outflow is expanding



The kelvin was previously defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water – where the solid, liquid and gaseous phases coexist at thermodynamic equilibrium. In November 2018, the member states of the International Bureau of Weights and Measures voted to redefine the International System of Units (SI), changing the definition of the kelvin as well as the kilogram, ampere and mole. The changes came into force on 20 May 2019, and the kelvin is now defined in terms of the Boltzmann constant (k), which has been given the fixed value of 1.380 649 $\times 10^{-23}$, expressed in joules per kelvin. The scale remains the same, with one kelvin being the same magnitude as one degree on the Celsius scale. 'Absolute zero' at 0 K is theoretically the lowest possible temperature, with a complete absence of thermal energy.

Roscosmos/NASA

NASA's Cold Atom Laboratory orbits Earth on the International Space Station.



NASA/JPL-Caltech

This graph shows the changing density of a cloud of atoms as it is cooled to lower and lower temperatures (left to right) approaching absolute zero (0 K). The emergence of a sharp peak confirms the formation of a Bose-Einstein condensate – a fifth state of matter – occurring here at 130 nanokelvin (one nanokelvin is one billionth of a degree).

at a speed of 590 000 km per hour, and spans a distance of almost four light years across the sky – equivalent to more than three trillion kilometres from end to end, which is about 21 000 times the distance from the Sun to the Earth.

Coldest place in space

In May 2018, NASA launched its Cold Atom Laboratory to the International Space Station, where it is being used to conduct fundamental physics research. More specifically, the lab can produce Bose-Einstein condensates (BECs) – considered the fifth state of matter after solids, liquids, gases and plasmas – and give researchers more time to study them.

BECs don't form naturally, but can be produced by cooling atoms in a dilute gas to ultralow temperatures, very close to absolute zero. As predicted in the 1920s by Albert Einstein on the basis of concepts formulated by the Indian physicist Satyendra Nath Bose, ultracold atoms move so slowly that they 'condense' into the same quantum state and start to behave like one continuous wave instead of discrete particles. This allows microscopic characteristics to be visible at a macroscopic scale.

On Earth, the BECs are pulled down by gravity and fall quickly to the bottom of any apparatus used to study them, limiting observation times to less than a second. Magnetic fields can be used to 'trap' the atoms and hold them still, but that restricts their natural movement. In the microgravity environment of the space station, BECs can float, which means they can be observed for longer. In its first two years of operation, the Cold Atom Lab has provided thousands of hours of microgravity experiment time to scientists on Earth – since the lab is operated remotely from NASA's Jet Propulsion Laboratory at Caltech – allowing them to repeat their experiments and make adjustments as needed. The ultracold temperatures are reached using a three-step process that involves laser cooling, evaporative cooling and adiabatic expansion. For a simple explanation, search YouTube for the video 'A recipe for cooling atoms to almost absolute zero'.

Coldest natural place on Earth

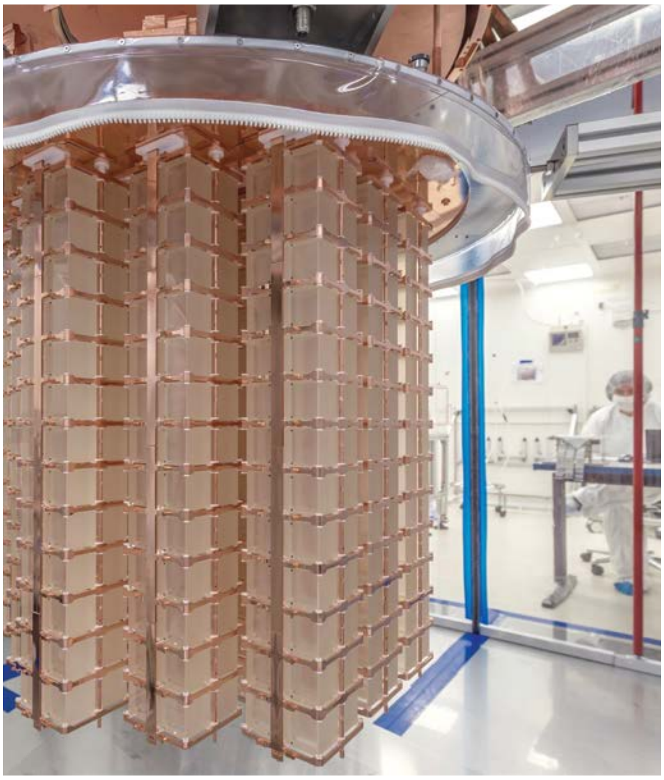
The coldest place on Earth is in Antarctica, but it's not at the South Pole. Nor is it at Russia's Vostok Station, which holds the record for the lowest air temperature (−89.2°C) ever measured by a weather station, on 23 July 1983. Using satellite data, scientists have found that about 100 sites on the high East Antarctic Plateau probably reach minimum air temperatures of −94°C during July and August, when the sun never rises above the horizon.

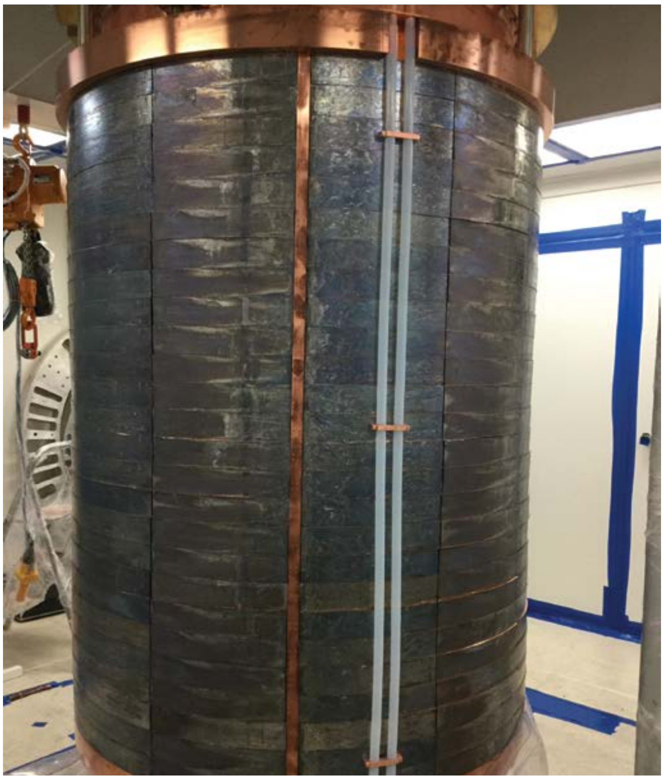
The scientists, led by Dr Ted Scambos of the National Snow and Ice Data Centre in the United States, analysed data for the period 2004 to 2016 collected by the MODIS instrument aboard NASA's Terra and Aqua satellites, as well as instruments on NOAA's Polar Operational Environmental Satellites. These measure the temperature of the snow surface, rather than the air above it, but by comparing the data with that collected by Vostok Station and three automatic weather stations in the vicinity, the scientists inferred that the near-surface (2 m) air temperature is 4°C warmer than the minimum −98°C snow temperatures.

These lowest temperatures occur in shallow depressions, approximately 2 m deep and less than 200 km^2 in area, at elevations of 3 800 m to 4 050 m. For the temperature to drop to these record levels, skies must be clear and calm, and the air must be extremely dry, because water vapour

NASA

Russia's Vostok Station on the East Antarctic Plateau holds the record for the lowest air temperature ever measured by a weather station, but satellite imagery has revealed colder spots in the surroundings.





CUORE Collaboration

The CUORE detector, made up of 19 copper-framed towers each housing 52 cube-shaped crystals, was assembled in a specially designed clean room to help protect it from contaminants. The outer casing includes a layer of radiation-depleted lead that was recovered from a 2 000-year-old Roman shipwreck.

blocks the loss of heat from the snow surface. Cold, dense air descends and pools above the surface, remaining in the depressions for several days. This allows the surface, and the air above it, to cool still further, until the clear, calm and dry conditions break down and the air mixes with warmer air higher in the atmosphere.

Coldest mountain 'heart'

In an underground laboratory deep beneath a mountain in Italy, an international team of scientists are cooling a chamber the size of a vending machine to a mere 10 millikelvin, or −273.14°C, to conduct experiments aimed at finding evidence of a rare particle process. The project is called CUORE, which is an acronym for the Cryogenic Underground Observatory for Rare Events, but also means 'heart' in Italian. The process it is designed to confirm is the hypothesised neutrinoless double-beta decay, which would provide insights into how matter was created in the universe.

Double-beta decay, which has already been proven, is a process that occurs in a few naturally occurring radioactive isotopes. It involves two neutrons – the uncharged particles in an atom's nucleus – becoming two protons and emitting two electrons and two antineutrinos. Antineutrinos are the antiparticles, or antimatter counterparts, to neutrinos.

By contrast, neutrinoless double-beta decay would not produce any antineutrinos. This is because they would erase each other in the decay process, proving that the neutrino is its own antiparticle, as the Italian scientist Ettore Majorana hypothesised in 1937. Discovery of this neutrinoless process would mean that a neutrino and an antineutrino, which are both electrically neutral, are essentially the same particle (called a Majorana neutrino). The underground facility is part of the Italian National Institute for Nuclear Physics (INFN), but the project involves scientists from some 20 institutions in Italy, the United States, France and China. The CUORE detector consists of 988 cube-shaped crystals made of a highly purified, natural form of tellurium dioxide. These are stacked in 19 copper-cladded towers, which are suspended within a tank enclosed by five others, like Russian nesting dolls. The detector is shielded from outside particles, such as cosmic rays constantly bombarding the Earth, by the 1 400 m of rock above it, and by thick lead shielding, which includes a radiation-depleted form of lead that was recovered from an ancient Roman shipwreck.

Coldest mountain peak in Africa

Mount Kilimanjaro in Tanzania is not only Africa's highest mountain, at 5 895 m above sea level, but is also the highest free-standing mountain in the world. It is a stratovolcano, built up from hardened layers of lava, ash and other pyroclastic material, and has three distinct cones. Two are extinct, while the youngest, Kibo, is considered dormant, having last erupted more than 150 000 years ago, although steam and sulphur are still emitted from its crater.

Kilimanjaro is situated only 370 km south of the equator, but air temperatures at the summit remain below freezing. Its snow- and ice-capped dome often appears to hover over the hazy, sunbaked African plains below, but it is this iconic feature that has become a 'poster child' for the effects of climate change.

Fallen snow compresses into thickened ice masses over many years, and those that flow are known as glaciers. Kilimanjaro had an almost continuous glacial ice cap in 1912, but by the 1980s this had been reduced to three

Air temperatures at the summit of Mount Kilimanjaro in Tanzania remain below freezing.

separate bodies of ice – the northern, eastern and southern ice fields. The retreat continued, and by 2011 only 1.76 m^2 of ice cover remained, representing an 85% loss over a hundred years. Today, it is considered highly unlikely that any ice body will remain after 2060.

Scientists from a number of countries are conducting research on this glacial retreat and its cause, using aerial photography, satellite imagery, laser scans, ground-penetrating radar, meteorological measurements and modelling studies. It is generally agreed that the loss of ice is not the result of increased air temperatures, but rather due to a decrease in atmospheric moisture, causing lower humidity. This not only means that there is less precipitation in the form of snowfall, but there is less frequent cloud cover too, exposing the snow and ice to more solar radiation. Some years, however, experience good snowfall, and this appears to be linked to broader patterns of climate variability associated with the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), also known as the Indian Niño or the Indian Ocean Zonal Mode. For example, warmer sea surface temperatures in the western Indian Ocean during the IOD positive phase raise atmospheric moisture levels, causing higher than normal precipitation in East Africa. El Niño and IOD also increase the frequency of tropical cyclones – intense storms that form over warm oceans – and these may cause heavy snowfall on Kilimanjaro as short-term events.

Coldest country in Africa

Lesotho is the country with the coldest temperatures overall, although the city of Ifrane in Morocco holds the African record for the lowest temperature ever observed, as recognised by the World Meteorological Organisation. Ifrane lies at an elevation of 1 665 m in the Middle Atlas mountain range, and a minimum temperature of −23.9°C was recorded at its meteorological station on 11 February 1935. But the whole country of Lesotho lies above 1 400 m – it is in fact the only independent state in the world that lies entirely above 1 000 m – while the highest point is the 3 482 m Thabana Ntlenyana mountain peak. With a mean elevation of 2 161 m, it is easy to comprehend why Lesotho is known as the 'Kingdom in the Sky'.

In June and July, minimum temperatures fluctuate around 0°C overnight, but rise to an average 15°C during the day. Snowfalls occur periodically, but research led by Professor Stefan Grab at the University of the Witwatersrand indicates that these were much heavier and more frequent during the first half of the 19th century. Back then, snow typically

NASA Earth Observatory

A satellite image from 11 August 2018 showing a blanket of snow over much of Lesotho.

remained in the Lesotho Highlands from May to September, but nowadays snow only lasts for an average of 10 days following individual snowfalls.

In a paper published in the Water Research Commission's journal, *Water SA*, Prof. Grab and co-authors note that the change in snow occurrence has a number of implications for the rural communities in the Lesotho Highlands. The more abundant snow of the past would have sustained their water supply during the dry season, but they have adapted to the change by building makeshift channels to divert water from springs. Herders also tend to leave sheep and cattle in the highlands all year round now, which depletes grazing resources and accelerates land degradation and soil erosion. And since the herders have become accustomed to light snowfall, they may be unprepared for periodic extreme events involving blizzards and deep snow, threatening their survival.

Coldest town in South Africa

Sutherland in the Karoo is considered South Africa's coldest town, with an average annual temperature of only 12°C. Winter brings occasional snowfalls and chilly overnight temperatures, dropping to an average minimum of 3°C during July. Less than 3 000 people live in the town, but it welcomes a steady stream of visitors because the South African Astronomical Observatory (SAAO) field station is perched on a hill 18 km away, at an altitude of 1 800 m. The area's relatively clear, cloud-free skies all year round, together with the lack of light pollution and city smog, provide ideal conditions for astronomy.

For this reason, the SAAO's field station was chosen as the location for the Southern African Large Telescope (SALT) – the largest single optical telescope in the southern hemisphere. It has an 11 m-wide primary mirror, made up of 91 individual 1 m hexagonal mirrors, and can detect light from objects a billion times too faint to be seen with the unaided eye. Construction was completed at the end of 2005, and scientific observations began in 2011, following a period of commissioning and performance verification. SALT is funded by a consortium of international partners from South Africa, the United States, Germany, Poland, India, the United Kingdom and New Zealand.

Apart from SALT, the site has three other optical telescopes owned and operated by SAAO – the 1.0 m and 1.9 m

Sue Matthews

The South African Large Telescope (SALT) building overlooks a winter wonderland at the SAAO field station near Sutherland.

Gregor Leigh

Postdoctoral researchers helped to set up the cryogen-free ^{3}He-^{4}He dilution fridge in the UCT Physics Department.

telescopes, as well as the newer 1.0 m Lesedi telescope, installed in 2017. In addition, there are a number of telescopes and instruments that belong to other research organisations, both local and international. A 3D interactive tour of the SAAO field station can be viewed at https://www.saao.ac.za/saao-vr-tour/tour.html.

Coldest facility in Africa

The Physics Department at the University of Cape Town claims the title of the 'coldest place in Africa' because it houses a cryogen-free ^{3}He-^{4}He dilution fridge that can be used to cool specimens to 10 millikelvin (mK), or −273.14°C. The fridge was purchased in 2014 at a 'cool' R6.5 million for the nanoelectronics research group to study material systems and electron transport, but it required repairs after arriving from the manufacturers in Holland in a damaged state, followed by operational refinement and the redesign of some components.

The refrigeration process in ^{3}He-^{4}He dilution fridges – used for the CUORE project too – relies on differences in thermodynamic characteristics of two isotopes of helium. A liquid mixture of these isotopes will separate into two phases when cooled below the tri-critical point of 867 mK. The lighter ^{3}He-rich phase, known as the 'concentrated phase', floats on top of the heavier ^{4}He-rich phase, which still contains up to 6.6% ^{3}He, so it is known as the 'dilute phase'. By pumping away ^{3}He from the dilute phase, more ^{3}He will be drawn down by osmotic pressure from the concentrated phase into the dilute phase to maintain the equilibrium concentration of 6.6%. The process of ^{3}He crossing the boundary between the two phases is endothermic, absorbing thermal energy, which has the effect of reducing the temperature of the mixture. The process can be likened to blowing on a cup of hot soup to cool it down – by blowing away the steam, more soup can evaporate, cooling what remains in the cup.

The 'cryogen-free' versions of such dilution fridges, also called 'dry' dilution fridges, do not require liquid helium for the initial cooling step. Instead, a mechanical cryocooler is used, and the refrigeration system is a closed-cycle design that continuously recirculates ^{3}He. This is beneficial because ^{3}He is extremely expensive and subject to periodic shortages in supply.

2020

Quest Volume 16 Number 3 2020

Academy of Science of South Africa (ASSAf)

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