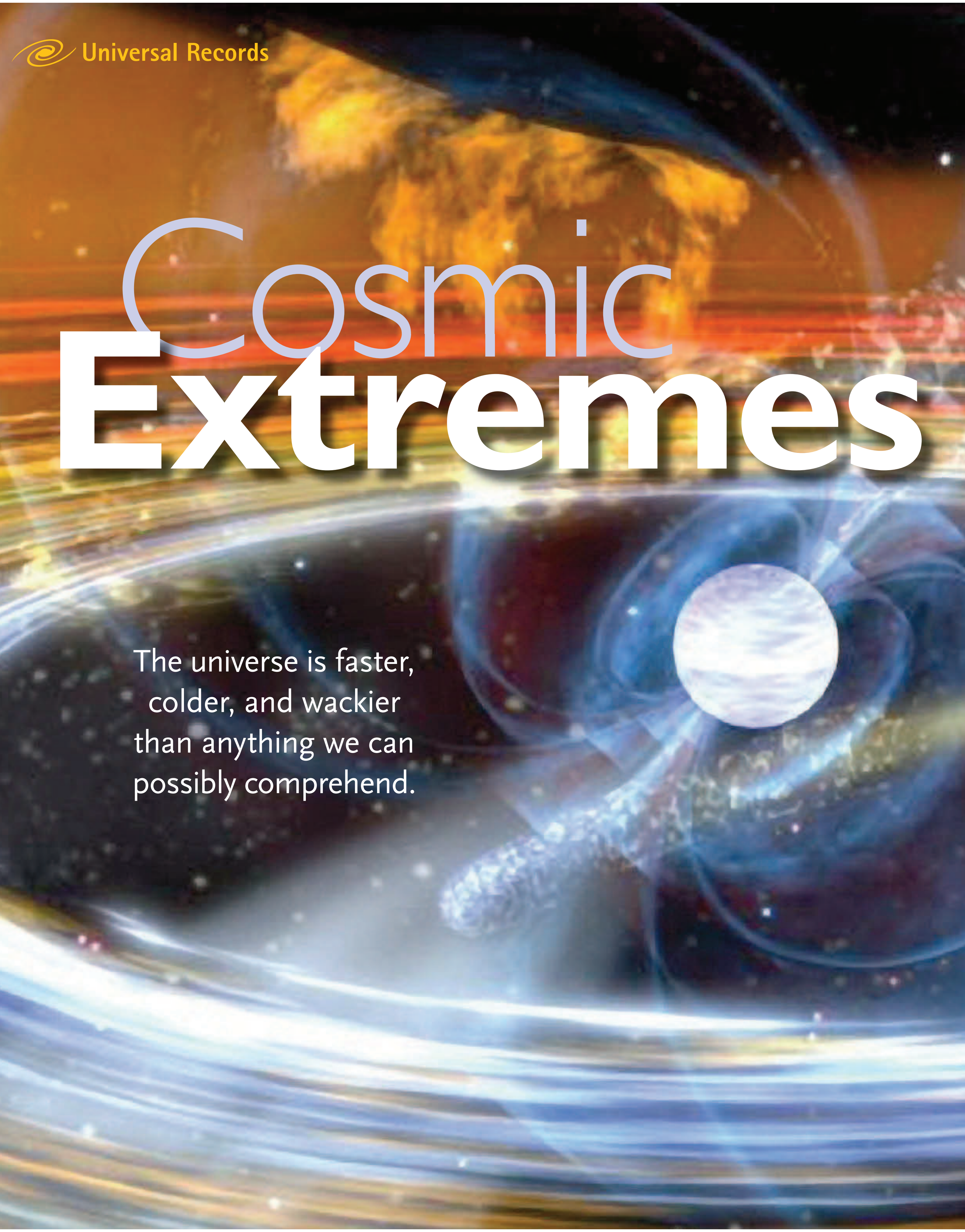
Cosmic Extremes



The universe is faster, colder, and wackier than anything we can possibly comprehend.


NASA

Bryan Gaensler

The universe extends far beyond our everyday experience in every imaginable way. But at the same time, it's truly remarkable that we can actually measure some of the universe's properties. What's more, we think we understand what most of these objects are, how they formed, and why they have their incredible characteristics.

Below I run through some of the concepts we experience on a daily basis: speed, temperature, gravity, density, and size. For each example there are extremes in our own experience: we all feel blazing heat and bitter cold, we see a jet plane speed overhead, and we watch a snail creep through a garden. But what are the absolute extremes that the cosmos can offer?

Fastest Spinning Star

Neutron stars are generally born spinning 30 to 50 times per second. But powerful magnetic fields gradually brake their rotation speeds as they age. Millions of years after its birth, a neutron star might spin only once every 5 to 10 seconds. This is still ridiculously rapid compared to most stars and planets, but it's glacially slow for a neutron star.

Bizarrely, some neutron stars can reverse their gradual spin-down. Despite now being hundreds of millions or even billions of years old, these stars spin more rapidly than at any previous point in their lives. The current record holder is a neutron star in Sagittarius named PSR J1748–2446ad, which is spinning 716 times per second! And what's more, this and dozens of other rapid rotators are not only spinning unusually fast, they are barely slowing down at all. A billion years from now, PSR J1748 will probably still be spinning more than 500 times per second — faster than a kitchen blender.

Such neutron stars were originally in a binary system with a normal star. If the orbit is sufficiently small, the neutron star's extreme gravity will strip gas off its companion's surface and drag it down toward its own surface. As this gas swirls downward to the neutron star and impacts its surface, it gradually adds its angular momentum, making the neutron star spin faster and faster. Given enough time, it can reach rotation rates of hundreds of times per second.

WHIRLING DERVISH This illustration depicts a pulsar that is siphoning material from a companion star. The gas forms a disk around the pulsar and eventually spirals in, gradually spinning up its rotation rate. A pulsar named PSR J1748–2446ad is the fastest-spinning star known; it rotates an incredible 716 times per second, near the theoretical maximum rate it can spin without breaking apart.

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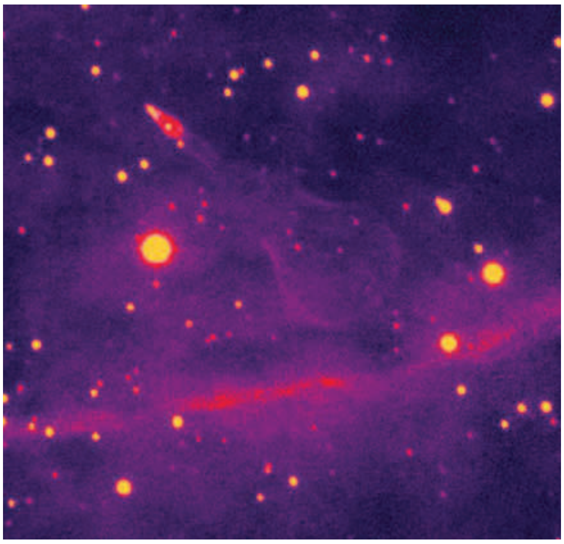


SHAMI CHATTERJEE / JAMES CORDES (CORNELL UNIVERSITY) / PALOMAR OBSERVATORY

Fastest Known Star:

Neutron stars also hold the record for the fastest-moving stars. If a supernova explosion were perfectly spherical and symmetric, debris would shoot out evenly in all directions, and the newly produced neutron star would sit stationary at the center.

But for reasons that we're still struggling to understand, these detonations are often asymmetric — material is blasted outward in some directions faster than others. Even if the asymmetries are minor, the explosion's energy is so large that if material is blasted away at higher speed in one direction, it can kick the newborn neutron star in the opposite direction at an extreme speed

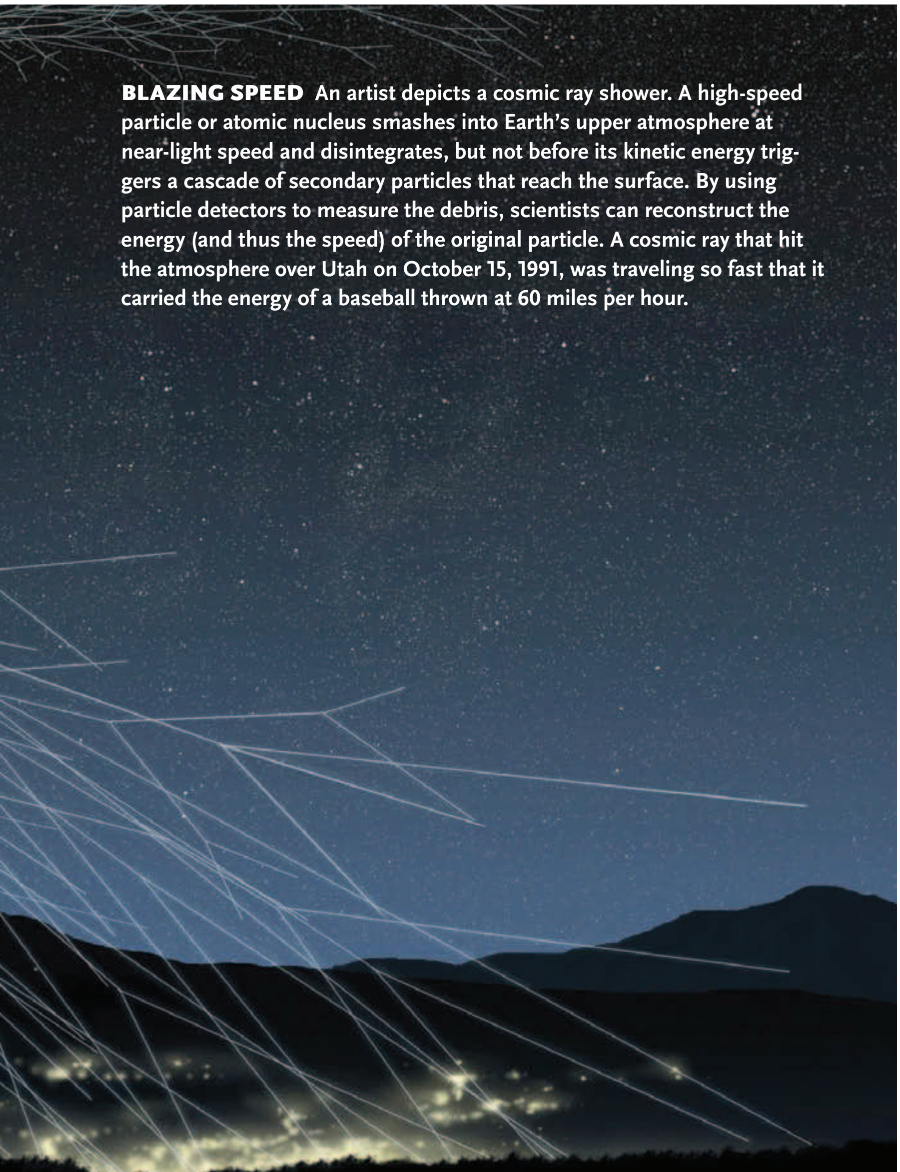
The fastest known neutron star, and indeed the fastest known star of any kind, is PSR B2224+65, an estimated 6,000 light-years away in Cepheus. PSR B2224+65 rotates at the comparatively sedate rate of 1.5 times per second. But what it lacks in spin it makes up for in sheer speed. If the distance estimate is accurate, the pulsar is racing through space at an incredible 3.6 million miles per hour. This is 4,700 times the speed of sound in Earth's atmosphere, 50 times faster than Earth's orbital speed around the Sun, and about twice as fast as the recently discovered population of hypervelocity stars that have been ejected from the Milky Way by a close encounter with the central supermassive black hole. PSR B2224+65 travels the distance from New York to Los Angeles every 2.5 seconds, and the Earth-Moon distance every 4 minutes.

GUITAR NEBULA *Top of page:* The pulsar PSR B2224+65 races through space at an estimated 3.6 million miles per hour, making it the fastest known star. As it plows through interstellar gas, it produces a bow-shock nebula resembling a guitar. This image was taken through a hydrogen-alpha filter by the 200-inch Hale Telescope on Palomar Mountain.

Fastest Known Object Other Than Light:

Trillions of cosmic rays crash into Earth every second. Cosmic rays are not actually "rays" per se; they are subatomic particles and atomic nuclei that typically travel at around 99% of the speed of light. This is faster than almost anything else in the universe, but it's still almost 7 million miles (11 million kilometers) per hour slower than light itself. But a tiny fraction of cosmic rays makes 99% of light-speed seem downright sluggish. This rare population of ultrahigh-energy cosmic rays approaches the fastest speeds possible under the laws of physics.

The definitive record for the fastest speed ever measured in the universe, except for light itself, was set at 1:34:16 a.m. local time on Tuesday, October 15, 1991, at the High Resolution Fly's Eye Cosmic Ray Detector near Dugway, Utah. A cosmic ray slammed into Earth's atmosphere, detonating into a spectacular shower of secondary particles. Using the pattern and extent of this debris, scientists reconstructed the speed at which this proton or atomic nucleus must have

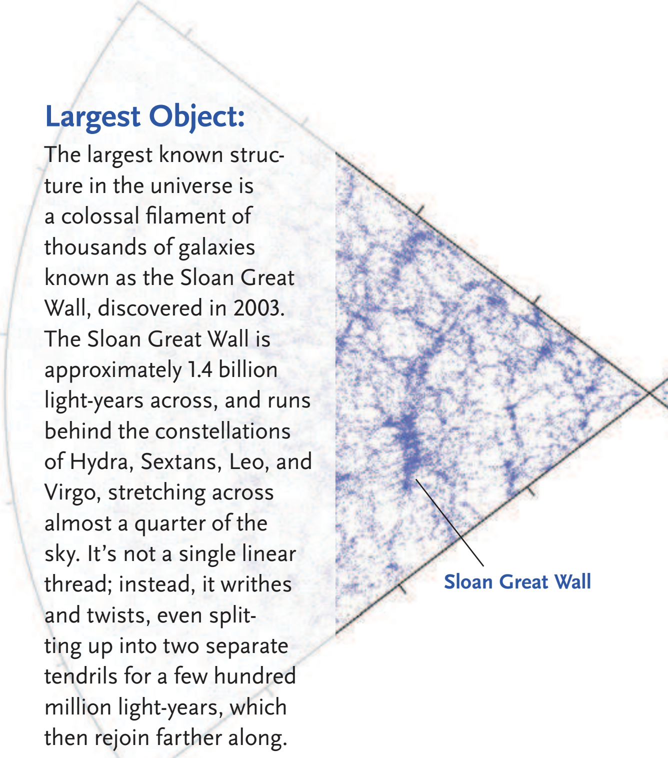


BLAZING SPEED An artist depicts a cosmic ray shower. A high-speed particle or atomic nucleus smashes into Earth's upper atmosphere at near-light speed and disintegrates, but not before its kinetic energy triggers a cascade of secondary particles that reach the surface. By using particle detectors to measure the debris, scientists can reconstruct the energy (and thus the speed) of the original particle. A cosmic ray that hit the atmosphere over Utah on October 15, 1991, was traveling so fast that it carried the energy of a baseball thrown at 60 miles per hour.

ASPERA / NOVAPIX / L. BRET

hit our planet, and the result was astonishing: it was moving at 99.99999999999999999999996% of the speed of light! Put another way, suppose this particle raced a light ray over a length of a million light-years. The light ray would beat the proton to the finish line by only about 1.5 inches (4 cm). Talk about a photo finish!

The cosmic ray seen in October 1991 earned its own moniker: the "Oh-My-God Particle." This particle's energy was staggering: more than 12 calories of energy when it arrived at Earth. To put this in perspective, consider the Large Hadron Collider (LHC) — the most powerful particle accelerator ever constructed. The LHC can boost subatomic particles up to a maximum energy of only around 0.0000002 calorie. Some unknown natural process in the cosmos can accelerate a tiny particle to an energy 50 million times greater than we humans can achieve. Such particles carry the same energy as a baseball thrown at 60 miles per hour.



Largest Object:

The largest known structure in the universe is a colossal filament of thousands of galaxies known as the Sloan Great Wall, discovered in 2003. The Sloan Great Wall is approximately 1.4 billion light-years across, and runs behind the constellations of Hydra, Sextans, Leo, and Virgo, stretching across almost a quarter of the sky. It's not a single linear thread; instead, it writhes and twists, even splitting up into two separate tendrils for a few hundred million light-years, which then rejoin farther along.

THE 2DF GALAXY REDSHIFT SURVEY TEAM

Fastest Orbiting Planet:

The record for the fastest known orbital motion of any planet goes to HD 80606b. A few times more massive than Jupiter, HD 80606b traces out a highly elongated, cometary-style orbit, completing its path around its parent star every 16 weeks. For part of its orbit, HD 80606b moves relatively slowly, and sits about as far from its star as Venus does from the Sun. But for a brief interval in every orbit, it swings inward, venturing 13 times closer to its star than Mercury's distance from the Sun. At closest passage, HD 80606b hits a top speed of 529,000 miles per hour, or almost 150 miles every second.

S&T: LEAH TISCIONE

Deepest Known Note:

The deepest note in space yet identified belongs to the galaxy cluster Abell 426, often nicknamed the Perseus Cluster because of its location in that constellation. Abell 426 is about 250 million light-years away.

Although we can never directly hear Abell 426's tune, we can see the pressure waves it generates. The gas that permeates the cluster, is incredibly hot, with a temperature exceeding 50,000,000°F. At this extreme heat, this gas becomes incandescent, and radiates extremely energetic and copious X rays.

In 2002 Andrew Fabian (University of Cambridge, U.K.) used NASA's Chandra X-ray Observatory to make a detailed image of the X-rays produced by Abell 426's hot gas. These observations surprisingly revealed a series of concentric ripples like those we see around a stone thrown into a pond. Fabian and his colleagues showed that these ripples correspond to places in the cluster where the gas density is slightly higher than the average. In the gaps between the ripples, they found that the gas density is slightly lower than average. Since a higher density means a higher pressure (and a lower density means a lower pressure), these ripples are oscillations in pressure, a giant sound wave that thrums throughout this vast cluster.

The origin of this racket is a supermassive black hole at the cluster's center. This black hole blasts out two oppositely directed high-speed jets of material that travel outward over millions of light-years at nearly the speed of light. These twin jets must force their way through the cluster's hot gas. Like a garden hose running underwater, the jets' collision with the cluster's gas generates a series of bubbles that inflate under the jets' power, and then break off and drift outward. As these bubbles expand, they shove the surrounding gas outward, setting up the pressure oscillations that ring through the cluster.

Determining the pitch of the corresponding note is relatively easy. The speed of sound in this 50,000,000°F gas is about 2.6 million miles per hour, and the spacing between each ripple is about 36,000 light-years. We simply need to divide the speed of the wave by the spacing of the ripples to determine the rate at which the pressure wave oscillates, and thus which note is playing. Fabian and his colleagues reached the conclusion that Abell 426 is humming in B flat.

But this B flat is unlike any note you've heard. The sound waves have an oscillation rate of once every 9 million years, which is 57 octaves below the B flat that's above middle C, or about 6,000 trillion times deeper than the lowest note that the human ear can hear. You would need to add another 635 keys to the left end of a piano keyboard to play a note this low!

NASA / CXC / M. WEISS

AN ULTRADEEP B FLAT The main image, from NASA's Chandra X-ray Observatory, shows how a giant black hole in galaxy NGC 1275 is affecting the entire galaxy cluster Abell 426. The black hole shoots out two powerful jets (not seen in this picture), which blow through the hot, X-ray-emitting intergalactic gas, creating bubbles that push aside surrounding gas. This energetic interaction generates sound waves that oscillate through the cluster and create ripples *(inset)*. In musical terms, the spacing of the ripples is a B flat 57 octaves below the B flat above middle C.

NASA / CXC / IOA / J. SANDERS, ET AL.

Strongest Electrical Current:

Abell 426's jets produce the gas vibrations associated with a deep note. But the jets from many other supermassive black holes travel unimpeded for a million light-years. Full of charged particles flying outward at high speeds, these jets carry the highest observed currents in the universe, typically at the level of 1 million trillion amps. Their power output is so large that in a single millisecond, one of these jets could provide enough electricity to cover humanity's energy needs for the next 20 trillion years.

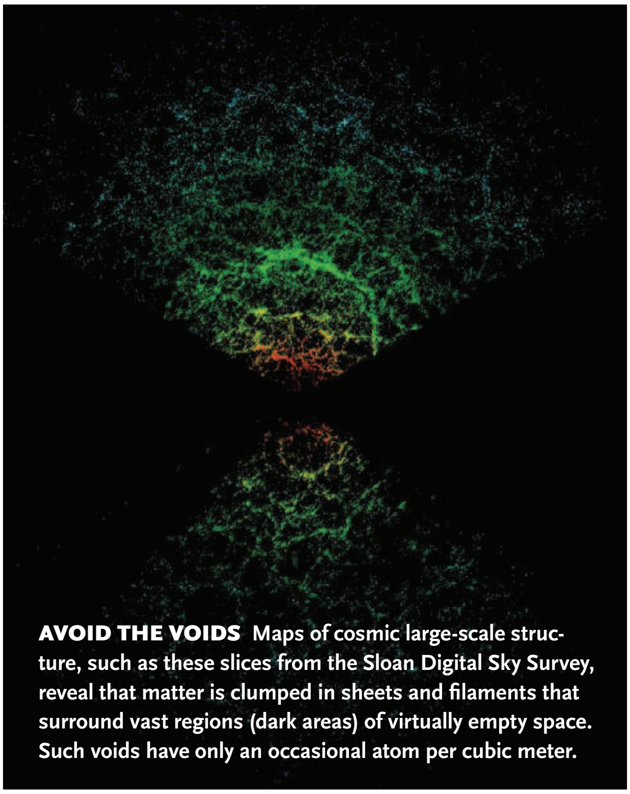
NASA / ESA / S. BAUM / C. O'DEA / R. PERLEY / W. COTTON / HUBBLE HERITAGE TEAM (STSCI / AURA), ET AL

Lowest Density

For centuries, laboratory scientists found clever ways to push to increasingly lower densities, creating ever more rarefied environments. The current state of the art, involving experiments that take several months, results in a gas density of just 500 to 1,000 atoms per cubic centimeter. By all reasonable measures, a gas in this state is a near-perfect vacuum. But the universe can effortlessly deliver far lower densities than this.

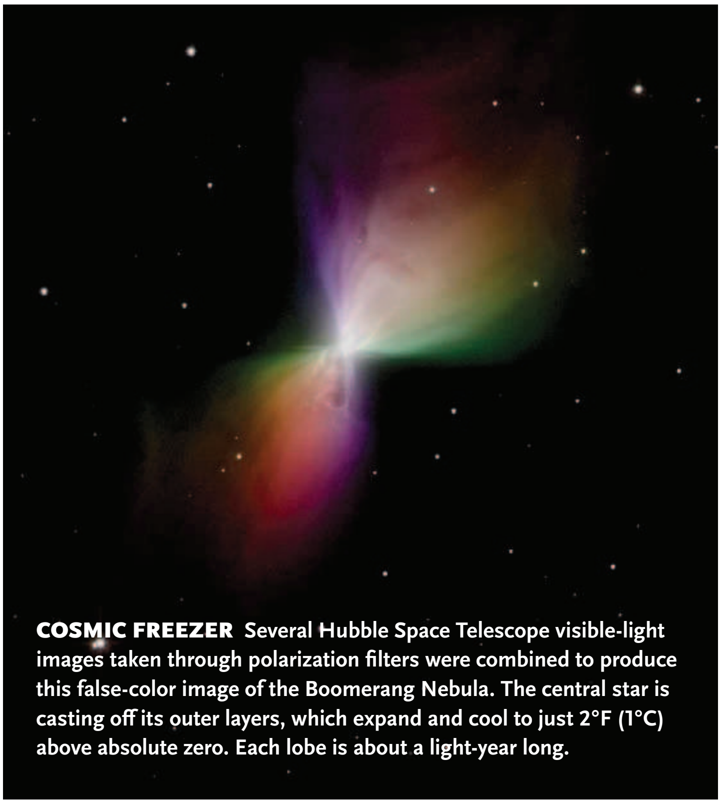
Galaxies are not scattered uniformly throughout the universe, but are arranged into a spectacular web of sheets, filaments, and shells. The walls of these intergalactic soap bubbles are busy agglomerations of stars and galaxies. But the bubble interiors are unimaginably, frighteningly empty. In these vast wastelands, often stretching across space for more than 100 million light-years, there is often nothing more than the occasional lone atom of hydrogen.

The density of a typical void is an incredibly desolate 0.00000002 atom per cubic centimeter. This is so sparse that even in a volume the size of a large room, you would be lucky to find a single atom. Put another way, if you were to grind a bowling ball into its individual constituent atoms, you would have to spread them over a volume 4 million miles across to achieve the same density as in a cosmic void. The massive surveys of the universe that astronomers have undertaken over the last 20 years have now revealed that these voids occupy around 90% of the volume of the universe, with everything else in the margins.



AVOID THE VOIDS Maps of cosmic large-scale structure, such as these slices from the Sloan Digital Sky Survey, reveal that matter is clumped in sheets and filaments that surround vast regions (dark areas) of virtually empty space. Such voids have only an occasional atom per cubic meter.

SLOAN DIGITAL SKY SURVEY COLLABORATION



COSMIC FREEZER Several Hubble Space Telescope visible-light images taken through polarization filters were combined to produce this false-color image of the Boomerang Nebula. The central star is casting off its outer layers, which expand and cool to just 2°F (1°C) above absolute zero. Each lobe is about a light-year long.

NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA) / JOHN BIRETTA

Coldest Known Place

The coldest temperature allowed by the laws of physics is absolute zero, at –459.67°F (–273.15°C). Laboratory experiments have reached temperatures within a billionth of a degree of absolute zero, but to reach these unbelievably frigid depths requires complicated and expensive equipment. The natural universe has no such equipment at its disposal, so how cold can it get?

The usual answer is the cosmic microwave background (CMB), the afterglow radiation from the Big Bang. The CMB has a temperature of –454.76°F, just 2.73°C above absolute zero, so it heats up space to a few degrees above the minimum possible temperature. But the Boomerang Nebula is even colder.

The Boomerang is a protoplanetary nebula, the result of layers of gas being shed by a star nearing the end of its life. The dying star that created this nebula had an extremely strong wind. For the last 1,500 years of its life, the star has been blasting this wind material into space at almost 370,000 miles (590,000 km) per hour. The star sheds about 70,000,000,000,000,000 tons of material through this wind every second. Besides its high speed, the stellar wind also expands rapidly as it flows outward. This rapid expansion causes a dramatic drop in temperature — essentially the reverse of the effect you experience when your bicycle pump heats up as you squeeze air into a tire.

The result is that the Boomerang Nebula's gas is at a bone-chilling –457.8°F (–272.1°C), even colder than the CMB. Although the central star powering the Boomerang Nebula is very hot, the combination of a high-speed wind and rapid expansion has produced the coldest natural place we know of in the universe, with a temperature even lower than the extreme chill of the surrounding space.

Weakest Gravity:

Black holes exert powerful gravitational forces, but what lies at the other end of the spectrum? How weak can gravity get? Or to rephrase the question more carefully, what is the gentlest pull that any object in the universe exerts, and yet is still able to force another body to orbit it?

Many small galaxies have correspondingly weak gravity. But if two low-mass galaxies can somehow come together in an isolated region of space such that they can move without being affected by larger galaxies, they can reach out with their feeble gravity and take up a fragile orbit around each other.

Of the many binary pairs of small galaxies we know of, the pair that is bound together most weakly is an obscure duo known as SDSS J113342.7+482004.9 and SDSS J113403.9+482837.4, or as I like to call them, Napoleon and Josephine. These two galaxies are 139 million light-years from Earth in Ursa Major. Napoleon and Josephine are 40,000 times too faint to see with the naked eye and, even through a telescope, they make a rather unimpressive couple. Each galaxy is about a thousand times less massive than the Milky Way, and both appear as unremarkable smudges in deep astronomical images.

But what's surprising about these two galaxies is the weakness of the gravity with which they hold each other together in their orbit. The larger of the two, Napoleon, reaches across 370,000 light-years to its companion with a gravitational attraction 900 trillion times lower than an apple experiences when it falls from a tree. If you hovered at the position of Napoleon and dropped an apple toward Josephine, you would have to watch the apple for 50,000 years for it to accelerate up to a speed of about an inch per second, slightly faster than a garden snail. Wait another 4 million years or so, and it would move up to around walking speed.

Not surprisingly, with this incredibly weak gravity between them, these galaxies take an eternity to orbit around each other. In fact, in the billions of years since these two galaxies formed, they have probably passed through barely one-fifth of their first orbit. And it's unlikely they will ever complete that orbit. The gravitational attraction between Napoleon and Josephine is so weak that it's merely a matter of time before some wandering galaxy interloper passes through their neighborhood and uses its stronger gravity either to capture these two into its own orbit, or to scatter this delicate pairing to the winds.

HEADING FOR DIVORCE The two circled galaxies that the author has nicknamed Josephine (top) and Napoleon appear as faint smudges in this Sloan Digital Sky Survey image. The galaxies are just barely bound to each other gravitationally. Other points of light in this field are either foreground stars or background galaxies.

SLOAN DIGITAL SKY SURVEY COLLABORATION

Extreme Cosmos

The numbers that measure cosmic extremities can at first seem difficult to comprehend. But on closer inspection, the universe's extremes become not only comprehensible, but turn out to be the vital keys needed to unlock the true wonder and elegance of the heavens. Despite the seemingly hopeless mismatch between our limited human imaginations and the size and complexity of the universe, it's astonishing that we understand so much of what we see. As baffled and cowed as we often find ourselves when confronted by the cosmos, it's perhaps humanity's ultimate accomplishment that we nevertheless can explain and appreciate the grandeur we observe in the night sky. ✦

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