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The Ultimate Mountaintop Astronomy Aboard Stratospheric Balloons

*"...the air through which we look upon the stars is in a perpetual tremor...
The only remedy is a most serene and quiet air such as may perhaps be
found on the tops of the highest mountains above the grosser clouds." --
Optics, Sir Isaac Newton*

Floating with the winds at heights higher than the Himalayas, the Swiss psychiatrist-cum-adventurer Bertrand Piccard had a view of the night sky that backyard astronomers can only dream about. His historical 19-day non-stop balloon flight around the world beneath the silvery Breitling Orbiter 3 last March had him hopscotching from one jet stream to the next, far above the lights of the cities, far above the clouds.

"It was absolutely fabulous," said Piccard, the grandson of balloon pioneer Auguste Piccard, the first man to enter the stratosphere. "We would shut off all of our lights at night and watch the multitude of stars shining above us. We were a little bubble floating around another bubble called earth, which is itself floating in a vast universe."

Such is the lure of the balloon, silent and majestic envelopes of air that lifted the Montgolfier brothers high above Paris 120 years before the Wright brothers wheeled their clumsy contraption onto the fields of Kitty Hawk. Science recognized the potential of ballooning immediately. Naïve yet resolute atmospheric explorers in the 1800s collected samples of air as high up as their naked lungs could take them. Others mapped the movement of the stars and planets during all-night voyages, seemingly without a care to what village they would land in the next morning. In the early 20th century, daylong balloonsonde missions brought the discovery of the cosmic rays, gamma rays and stratosphere itself. In the pre-Apollo years, balloons carried aeronauts to the brink of space.

Balloons, as playful as they seem, remain poised at the forefront of science. Astronomers and physicists today envision floating, retrievable observatories stationed four times higher than any passenger jet could dare venture. Their goal is to develop balloons capable of staying afloat for a hundred days or more at altitudes of nearly 40 kilometers. At that height, less than a hundredth of a percent of the atmosphere remains above, and we will have reached the summit of the ultimate mountaintop.

It seems fitting, then, that Bertrand Piccard and his crewmate, Brian Jones, have retired their tiny gondola to the National Air and Space Museum, where it rests with the *Wright Flyer*, the *Spirit of St. Louis* and the Apollo 11 command module. For like these past triumphs of aviation, the landmark balloon flight around the world is but a sign of fantastic things to come.

To Push or Pull

On August 11, 1999, Japanese researchers from the University of Tokyo were camped out in the soupy mosquito-rich marsh of Lynn Lake, Manitoba. This far north, they knew, the earth's magnetic field would kindly direct travel-worn charge particles from galaxies unknown into the welcoming arms of their balloon gondola. The Japanese have come in search of antimatter, an annual pilgrimage since 1993. They plan to do the same in 2000.

The 1999 balloon launch went off without a hitch -- and without a sound. The silence, in fact, was as magnificent as the deafening power of the Chandra X-ray Observatory's Cape Canaveral shuttle launch just weeks before. Now, NASA's largest balloon, 60 storeys high and 40 million cubic feet in volume, was lifting a 2.5-ton antimatter collector to a height of 37 kilometers. The launch seemed almost feminine compared to the testosterone-and-fuel-driven rocket launches for which NASA is known. But the Japanese team wasn't interested in poetics, just good science.

"The discovery of anti-helium would be stunning," said Shuji Orito, who leads the project known as BESS (Balloon-borne Experiment with a Superconducting Solenoidal magnet). Just one little anti-helium particle in their bag of anti-protons and other cosmic rays would point to the existence of entire antimatter galaxies. "Low-energy charged particles such as anti-helium are incident only into the polar regions," said Orito.

"where balloons can reach," but where satellite or space station orbits cannot.

Orito hasn't found any anti-helium yet. "Nevertheless," said Jonathan Ormes, a NASA astrophysicist who analyzes BESS results, "we are very excited every year when we check the latest data hoping to find the first 'Ambassador from the Anti-World.'"

To push or to pull, that is the question. And scientists are increasingly opting for the latter. Compared to a rocket launch, the balloon platform is a fraction of the cost; the cargo can be much heavier and unwieldy; and the instruments can be retrieved, tinkered with, and sent up again. Tinkering, in fact, has been key to BESS' durability. The first year only harvested a few antiprotons; subsequent adjustments have brought the catch to nearly a thousand.

A balloon payload also doesn't require the lengthy and rigorous testing and the expensive shock padding that a rocket launch does. "The first thing you do to a delicate satellite when you launch it on a rocket is shake the hell out of it," said Jack Tueller, project scientist for NASA's Ultra-Long Duration Balloon project. "This is like putting it on the back of a truck and driving around the world a couple of times." With a balloon launch, he said, there is virtually no shaking, and the instrument doesn't need to be folded into the shroud of a rocket. "If something does go wrong," Tueller said, "you can retrieve the instrument and launch it again."

For Tueller, the balloon is not just the poor man's rocket. He said that for a variety of science, the balloon platform is simply more practical. Tueller has even come up with an interesting pound-per-day comparison to rocket launches. A Pegasus rocket could carry 500 pounds of equipment for two years in space; a balloon could soon carry 3,000 pounds for 80 days. That's on the same scale. The cost of a balloon platform, however, is staggeringly lower. The 400-kilometer jump from a high-altitude balloon to a stable low-earth orbit packs on millions of dollars in extra costs and months, if not years, of development planning.

Thus, lower cost and flexible launches make the balloon platform the perfect test bed for new technologies. Elbow deep in balloon projects, Tueller also leads the effort for InFOC μ S, an instrument that will provide for the first time focusing optics for hard x-rays. This telescope will have an 8-meter focal length with a new type of "gamma-ray CCD" made from CdZnTe crystal, providing up to 30-arcsec angular resolution for X-rays at

65-80 keV. There are fewer pixels than what is on a CCD (only 64x64), but the energies are greater than optical and soft X-ray photons. Such technology is a key component of NASA's Constellation-X satellite, way down the pike in 2008. InFOCUS will fly on a balloon in June, 2000, and will fly many times after that to work out the kinks. Balloons, Tueller said, fly current technologies today.

Bread and Butter Ballooning

The bread and butter of scientific ballooning these days is essentially the same as it was a hundred years ago: cosmic-ray, gamma-ray and atmospheric studies. The atmosphere shields much of the universe's high-energy radiation and wandering particles from reaching the Earth's surface (see chart), so scientists need to go up into the stratosphere or space to collect them.

Cosmic rays, chunks of atoms that bombard the earth at nearly light speed, are as mysterious now as they were when German physicist Viktor Hess first discovered them on his precarious balloon flights in 1912. Some of these atomic particles, at 10^{20} electron volts, carry nearly as much kinetic energy as a major league fastball. Where do these particles come from, and what histories can they share?

One cosmic ray historian is the Isotope Magnet Experiment, or ISOMAX, an instrument that measures beryllium-10 much like an archaeologist measures carbon-14. Radioactive ^{10}Be has a half-life of 1.5 million years and decays into the more stable ^9Be . The ratio between the two, therefore, can reveal how long it takes for cosmic rays to reach the earth. Also, beryllium is solely produced by fragmentation of heavier elements, created by collisions in the interstellar medium, and serves as a tracer of the matter it has traversed. At two tons, though, ISOMAX would cost up to \$100 million to launch into space, requiring a Space Shuttle deployment. The ISOMAX superconducting 10,000-gauss magnet alone is over a thousand pounds. (They store ISOMAX in its own isolated shed with a red light warning those with pacemakers to stay clear.) The balloon launch costs only about \$200,000, about a quarter of the annual ISOMAX budget. ISOMAX is set to fly again in August; by autumn, the team hopes to announce the long-awaited results from the first flight in 1998.

Atmospheric experiments fly 10 times higher than weather balloons. Geoffrey Toon (JPL) used a balloon last year to help prove that the ozone loss observed each summer over the North Pole is a natural phenomenon. His team flies the 1,800-pound JPL MkIV experiment at 39 kilometers for about a day at a time. Toon found enhanced amounts of stratospheric nitric oxide (NO) in the Arctic summer, which eats away ozone. The culprit is the 24-hour sunlight, which prevents the normal nighttime conversion of NO and NO₂ into ozone-friendly N₂O₅.

New Observations of Ancient Radiation

Some of the more exciting balloon experiments now being flown concern the cosmic microwave background (CMB) radiation. The CMB is the remnant heat from the Big Bang, which has cooled down considerably since that initial spark to a chilly 2.728 degrees above absolute zero. Observations of the CMB take us back to about 300,000 years after the Big Bang, billions of years earlier than any of the light that Hubble can detect. More importantly, accurate measurement of the CMB yield the value of Ω , the total density of all matter in the universe.

In 1990, the Cosmic Background Explorer (COBE) became the first satellite to nail down temperature fluctuations in the CMB. Such fluctuations, however slight, point to density differences in the tiny ball of the newly expanding universe that later gave way to galaxies. NASA's successor satellite to COBE is the Microwave Anisotropy Probe (MAP), which will be launched in 2001 and followed by the even more sensitive ESA Planck mission in 2007. Cosmologists just couldn't wait, though. Over the past few years, they turned to balloon experiments that carried detectors up to 100 times more sensitive than those flown on COBE.

BOOMERANG, a clever acronym for Balloon Observations of Millimetric Extragalactic Radiation AND Geophysics, is an international effort led by Andrew Lange at Caltech. The experiment flies over Antarctica every January. This can be more expensive and riskier than North American flights, due to the location and tricky winds. Yet the constant daylight and lack of day-night temperature fluctuations allow the pressurized balloon to stay afloat longer to collect more data. The January 1999 effort was a textbook flight, with the balloon traveling 8,000 kilometers around the pole and landing only 50 kilometers from the launch site 10 1/2 days later.

The BOOMERANG results, released in April 2000, made headlines. The data provide the clearest image yet of the early universe, an era when the first atoms formed, allowing light from the big bang that had been absorbed in a soup of subatomic particles to finally shine through. The data also support the notion that we live in a flat, Euclidean Universe that will expand forever, Lange said. BOOMERANG will fly once again in January 2001, this time looking for polarization, as opposed to temperature fluctuation, which some theorist predict could trace the gravitational wave background from the inflationary period in the moments that followed the Big Bang. The team is still waist-high in data from this year's flight, with enough number-crunching to keep a supercomputer busy for several months straight.

Paul Richards (UC Berkeley) leads the MAXIMA (MAX Imaging Array) experiment, which has made two overnight flights above Palestine, Texas, and will fly again in October 2000. He said his team is also overloaded with data analysis. Whereas about 10 months of COBE observations captured the whole sky in 5,000 pixels, three hours worth of MAXIMA balloon data paints a 30,000-pixel picture. MAXIMA finds that the universe is filled with 5 percent ordinary matter; the remainder is either cold dark matter, the unseen mass that holds galaxies, or dark energy, a mystifying repulsive force that seems to be accelerating the expansion of the universe. The results released in May show spectacular agreement to BOOMERANG, a good confirmation that we are getting the science right, Richards said.

NASA's TopHat and the international BAM (Balloon Anisotropy Measurement) experiment, two other efforts to map the CMB, did not in 1999 as scheduled for technical reasons. They are now waiting a full year to catch the right winds for their particular type of balloon flight -- a blow to these teams racing to collect prime data before the MAP launch. The yearly delay due to wind cycles is one downside to the ordinarily flexible balloon launch platform. All is certainly not lost, however, according to BAM leader Mark Halpern (University of British Columbia). He said no balloon can truly compete with MAP, but balloon-based CMB data, regardless of when it is collected, is an inexpensive and invaluable crosscheck to MAP data.

It's a Bird! It's a Plane! It's a Telescope!

Although the atmosphere kindly allows visible light to penetrate, astronomers cannot help but take advantage of clearing 99% of the air above us. Stratoscope I and II, flown in the 1950s and 1960s by the late Martin Schwarzschild (Princeton University), were essentially precursors to the Hubble Space Telescope. The first, a 30-cm solar telescope, obtained extraordinarily sharp pictures of the corona; its successor, a 90-cm mirror lofted at heights of over 32 kilometers, made several photographs of planets and star systems with a resolution close to a tenth of an arc-second. Some astronomers today are striving for millisecond-arc optical imaging, an equivalent of a 10-meter ground-based telescope without the need for corrective optics voodoo, which could outdo Hubble.

The French PRONAOS (Le Programme National d'observations Submillimetriques) obtains up to 5-arcsec resolution in the infrared with its 2-meter wide telescope. At 40 kilometers high, PRONAOS clears the water molecules in the atmosphere that make a mess out of ground-based infrared observations. In this regard, PRONAOS is a precursor to the Space InfraRed Telescope Facility, an orbiting 85-cm telescope and the final installment of NASA's "Great Observatories."

The Solar Disk Sextant and the Flare Genesis Experiment are two of many sun chasers. Flare Genesis is an 80-cm aperture telescope that measures the sun surface magnetic fields and motions. With 10-day flights over Antarctica, the experiment is searching for the solar conditions that lead to solar flairs. The telescope provides 0.2-arcsec resolution, compared to SOHO's 4-arcsec resolution. Solar Disk Sextant has gone far in accurately determining of the shape of the sun. The experiment now hopes to graduate to Earth orbit, however, because temperature changes from the ground through the troposphere and stratosphere limit the instrument's sensitivity.

Inflatable Sandwich Bags

It is a little known fact that the United States mainland was bombed during WWII. In retaliation to the Allied-led Doolittle Raid on Tokyo on April 18, 1942, Japan spent the next two years constructing 9,000 balloons of paper and silk, for rubber was too precious to sacrifice. Women and children were recruited to turn mountain root vegetables into glue for the balloon fabric. During a five-month "bombing" campaign starting on Nov. 3, 1944, Japan launched these backyard balloons with

real anti-personnel and incendiary bombs into the high altitude winds that would carry them more than 9,500 kilometers eastward across the Pacific.

Nearly a thousand reached the States, some setting off forest fires. On May 5, 1945, six picnickers were killed in Oregon when a balloon bomb they dragged from the woods' exploded. These were the only known fatalities occurring within the United States during WWII as a direct result of enemy action.

Paper and silk were the fabrics that carried countless balloon adventurers to altitudes of 9,000 meters for more than 150 years. By the early 20th century, rubber and new synthetic fabrics being developed at Dow Chemicals were lifting balloons higher and higher. Today, fabrics about the thickness of plastic sandwich bags carry 3,000-pound loads to the fringes of space.

The NASA National Scientific Balloon Facility in Palestine, Texas, is behind most of the world's high-altitude balloon launches. From the Antarctic to the Canadian flatlands and a few deserts in between, the NSBF sets afloat about 30 balloons a year to heights of 30 to 55 kilometers. Balloons come in five classes, ranging in size from 11 to 40 million cubic feet, the largest roughly 170 meters in diameter when fully inflated (large enough to hold a fleet of Boeing 747s).

Balloon launches usually involve a crane and a dozen or so personnel. The crane keeps the payload a few feet off the ground for the launch. The balloon remains stretched out along a runway. As the balloon slowly inflates with helium, it rises above the payload. The crane follows the balloon as it passes over the payload, keeping the payload from dragging along the ground. As the balloon begins to lift the payload, the crane lets go. The balloon will climb for several kilometers before fully inflating. High into the clouds, what looks like a long, thick rope connecting the balloon to the payload is actually uninflated balloon material.

The launch can be exhilarating, yet most scientists will tell you the wait can be fantastically boring. Balloonists are at the mercy of the wind and the rain. A launch could go off like clockwork, or it might be postponed day-by-day for two weeks. Hacky-sack and pinochle only whittle away the time so far in the 50 degree Celsius heat of Australia's Alice Springs.

Countdown to the 100-Day Balloon

Steve Smith and Henry Cathey are busy these days blowing up balloons and popping them. They lead a team of engineers at Wallops Flight Facility constructing 100-day balloons, the essential goal of the Ultra-Long Duration Balloon project. An extended balloon platform opens up endless possibilities, such as a floating Keck or even communication towers. The first ULDB flight with real cargo (a cosmic ray experiment called TIGER) is set for December 2001.

Currently, high-altitude balloon flights last only a couple of days. The main problem is temperature fluctuations from day to night. The sun hits the balloon; gas warms up and expands; and the excess expanding gas is vented out to the atmosphere. Sun sets; gas cools; the gas contracts; balloon volume decreases; and the balloon sinks. Balloonists can buy a day to two by dropping ballast at night. They can fly up to 22 days in Antarctica, where summer days (or nights) last half the year and there is no day/night temperature fluctuation. But eventually the balloon comes down.

The ULDB is a sealed, super-pressure vessel that can maintain pressure differences at day and night. As such, Smith's team needed to find a tough new material and design that could resist pops and tears and hold up to the prolonged UV exposure in high altitudes. The ULDB material -- about the thickness of a sandwich bag at 0.0381 mm -- is an extruded polyethylene film with a high-density layer in between two linear low-density layers, "like a slice of salami on soft white bread," said Cathey. The "salami" part provides strength; the "bread" provides surface toughness and enables a secure seal between the sheets of film that form the balloon envelope. The unique pumpkin-shape design shifts most of the stress to the tendons. This has allowed engineers to use a lighter, more durable material than what is used on spherical balloons to support 3,500-pound payloads.

Smith's main worry is trajectory control, the ability to prevent the balloon from drifting over unfriendly countries or controlling its direction in general to maximize the science of a particular experiment. "Trajectory control is the biggest technological leap for the ULDB," said Smith, the ULDB project manager. "It could make or break things for flying only 60 days or for 100 days." Another concern is fine pointing for arc-second imaging, for balloons at that height tend to rotate. Such issues will likely be worked out, Smith said, in the first couple of years following the test flight.

Spying on Extra-Solar Earth-Sized Planets

NASA's Olympus Study Group, named after the legendary mountains on both Earth and Mars, identifies ambitious scientific missions and the corresponding technology in both earth and space science that would benefit from this long duration balloon platform, according to group leader Robin Mauk, a systems engineer at Goddard. She said that early proposals to the ULDB project include extra-solar planet searches and the first hard x-ray surveys of the entire sky. A promising commercial application is station keeping, essentially floating cell phone towers and other telecommunications bases that currently blight the landscape.

Holland Ford (Johns Hopkins University) and Larry Petro (Space Telescope Science Institute) hope to fly a 2.5-meter optical telescope and coronagraph at a height of around 36 kilometers to search for Jupiters and perhaps Earths around the brightest stars within 10 parsecs. Their instruments could provide four orders of magnitude improvement over HST WFPC-2 and the biggest ground-based observatories. Harvard's John Grindlay envisions southern and northern balloon launches for an X-ray telescope called EXIST-LITE, which would survey the 20-600 keV X-ray band with 10 times the sensitivity of the upcoming INTEGRAL mission.

Another missions slated for the ULDB is SOAR, a far-infrared telescope with diffraction-limited resolution over a field view of 6.25 arcmin -- a precursor to a 3-meter balloon-borne telescope. Led by Giovanni Fazio and Gary Melnick (SAO), the goal of SOAR is to detail the birth and evolution of galaxies, as well as stars in our own galaxy.

Balloons Over Mars

Plans for extraterrestrial balloons are also afoot. Mercury and Pluto are the only planets that do not have an atmosphere to support balloon flights. The rest, as well as a few moons, are fair game. In 1985, the Soviets floated two balloons over Venus for 48 hours, gathering data on atmospheric temperature, pressure and winds. NASA and ESA are now considering plans to send balloons to Venus, Mars and Saturn's Titan. Ideas include collecting samples of the new worlds with drag ropes or probes and letting balloons wander with cameras snapping images of the surface with resolution 10,000 times greater than satellite shots.

Planetary ballooning is in many ways opposite from Earth ballooning. Balloons are dropped over the planet, not launched. The trick is to get below the clouds for surface imaging, not above for stargazing. And as Tueller jokes, there's no worry about crossing borders. On Earth, tight control over trajectory is a top priority. Over Mars, wandering is encouraged. "The winds will carry the balloon where the scientists never thought to go, and this is probably a good thing," said Tueller. "Who knows what we will discover."

As funding for astronomy dwindles and the competition for observation time heats up, more astronomers may turn to balloons. Far above the Keck telescope on Hawaii's Mauna Kea, higher still than the hostile snowcapped peaks of Mt. Everest, there exists a 40-kilometer summit that will place their telescopes above 99% of the atmosphere. With the prospect of 100-day and even 1,000-day balloons, the climb to the summit is more and more tempting. Surely, given enough cash, most astronomers would opt for a lunar base or a platform beyond the Earth. Until then, many seem happy to settle for a stratospheric mountaintop.

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