to remove from Sandage's near sample of seven calibration supernovae the three that predate the introduction of modern electronic photometry in the 1970s. "Our methods can't handle the complexities of the old photographic plates," Kirshner told us. It just so happens that these old supernova records are the ones that push H_0 down. "So simply cutting out the three old ones," Kirshner explained, "already brings Sandage's H_0 up to 62, even before we apply our light-curve corrections." The Cerro Tololo group also argues that just by calibrating with Cepheids one introduces a slight bias toward low H_0. Cepheids are found mostly in spiral galaxies; and, the group claims, the brightest type Ia supernovae occur in spiral galaxies.[3]

The scatter of observed apparent magnitudes around the straight line in the Hubble plot is a measure of how good the standard-bomb conjecture really is. "We must be doing something right," Kirshner told us, "because when we apply the corrections to the assumption that all the peak luminosities are the same, the scatter around the Hubble line is cut in half."

Other yardsticks

No one would argue that type II supernovae are anything like standard bombs. Nonetheless they too can be exploited to measure the Hubble constant. Kirshner is also in the type II business. He and collaborators have developed the so-called expanding-photosphere method for estimating the intrinsic luminosity of a type II supernova from the time dependence of its optical spectrum. From spectroscopic records of a dozen type II supernovae, going back to 1968, the group gets an H_0 of 73 ± 7 km/(s·Mpc), quite independent of any Cepheid distance measurements.

The most prominent of the non-supernova techniques that have consistently put H_0 above 80 km/(s·Mpc) is the Tully–Fisher method, which exploits an empirical relation between the intrinsic luminosity of a spiral galaxy and its rotation speed, as measured by Doppler broadening. Another widely used galactic technique that generally puts H_0 above 80 is the measurement of surface-brightness fluctuation. The distance to a galaxy of given apparent surface brightness can be gauged by its observed graininess: The more distant a galaxy, the harder it is to resolve individual stars and therefore the smoother the galaxy looks.

All such "secondary distance indicators," just like the supernovae, have to be calibrated, or at least confirmed, by comparison of nearby exemplars with primary yardsticks like the Cepheids. A principal function of the Hubble telescope's ongoing "Key Project" is to measure Cepheid distances to a variety of galaxies in order to improve the reliability of all the secondary yardsticks, including the supernovae. (See PHYSICS TODAY, December 1994, page 19.) Wendy Freedman, Sandage's neighbor at the Carnegie Observatories, is one of the leaders of the Key Project. "We don't know why Tully–Fisher and the supernovae give different results," she told us. "The Key Project's goal is to understand these systematic discrepancies and pin down the Hubble constant to within 10 percent."

Sandage and Tammann, on the other hand, claim to know already what's wrong with the Tully–Fisher method.[5] "It seriously overestimates the Hubble constant," Sandage contends, "because of a selection bias at large distances in favor of atypically bright galaxies." As we go to press, Tammann and Sidney van den Bergh (Dominion Astrophysical Observatory, Victoria, British Columbia) are about to undertake a commemorative debate on 21 April, the anniversary of the historic 1920 debate between astronomers Harlow Shapley and Heber Curtis. The argument 76 years ago was whether some of the nebulae might be other galaxies, far beyond the Milky Way. This year's debate, on the value of the Hubble constant, will be in the very same auditorium of the National Museum of Natural History in Washington, DC. The subject in contention also remains essentially the same: the scale of the universe.

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Model Sheds Light on a Tragedy and a New Type of Eruption

Ten years after a natural disaster in Cameroon killed 1746 people, a new model adds support to the hypothesis that the culprit was a previously unknown type of nonvolcanic eruption.

For several hours on the night of 21 August 1986, a massive jet of gas and water erupted from Lake Nyos, a remote, deep volcanic lake in the uplands of northwestern Cameroon in West-Central Africa. Reaching a height of over 100 meters, the heavy, lethal gas displaced the air below it and swept down the slope, asphyxiating 1746 people in the villages below the lake.

In preliminary investigations after the tragedy, the violence of the Lake Nyos event quickly became apparent. In the village of Lower Nyos, 3 km below the lake, only 6 of over 1000 inhabitants survived the disaster; deaths from asphyxiation were also common at Subum, more than 10 km distant. Wave damage along most of the southern shore reached 25 m above lake level and over 80 m at one point.

Despite the violence of the event and the volcanic origin of the lake, much of the evidence did not support volcanism as the direct cause of the tragedy: The sediment on the lake bottom remained undisturbed; the lake waters remained cool; and water samples contained almost no volcanic gases other than carbon dioxide and, at least below the upper 10 meters, almost no suspended sediment. (See the cover of this issue.) Furthermore, the gas cloud that engulfed the valley below the lake was cool and left no evidence of having contained caustic volcanic gases. What was perhaps most important, researchers found the lake to be highly stratified, with a distinct "chemocline," across which a dense, lower layer, rich in CO_2 and ions, rarely mixed with the lighter, fresher water above it.

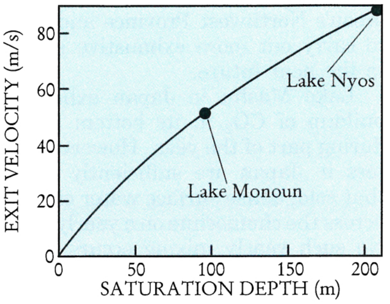
By the end of 1986, most researchers were blaming the Lake Nyos disaster on a previously unknown type of eruption—a "limnic," or lake-water eruption, in which some disturbance raises CO_2-saturated bottom water across a chemocline to a region of lower hydrostatic pressure. The water degasses explosively because CO_2 solubility decreases with decreasing pressure—the same reason that soda in a bottle fizzes when the cap is removed. Researchers determined that a limnic eruption had probably also caused a similar disaster at Lake Monoun, 95 km south of Lake Nyos, that resulted in 37 deaths on 15 August 1984.

Limnic eruption

Gradually, researchers were able to outline broadly how such a limnic eruption might proceed: Gas, forced out of solution in a body of cooling magma below the lake, would dissolve in water and flow along rock fractures. By the time the water reached the lake, the dissolved gas would be largely depleted of its reactive components, becoming 98–99 percent CO_2. Because of its greater density, the CO_2-rich water would remain near the lake bottom, unable to mix with the fresher water above it. However, any disturbance that raised saturated bottom water into the lower-pressure, shallow regions above would cause the dissolved gas to "exsolve," or bubble out of solution. As buoyancy forced the resulting gas–water mixture upward, CO_2 would continue to exsolve, further increasing the mixture's buoyancy, and additional dense CO_2-rich bottom water could be siphoned up into the eruption conduit, sustaining the reaction. Skeptics countered that it was by no means clear how such a process would be sustained and limited to only a portion of the lake like the eruption reported by eyewitnesses at Lake Nyos.

Still, a decade of observing the posteruption evolution of Lake Nyos has confirmed the limnic eruption hypothesis as the most likely explanation of the tragedy and has allowed researchers to reconstruct the probable conditions in the lake just prior to the eruption. By assuming that the lake's posteruption composition resulted from a mixing of the bottom-water and freshwater layers during the eruption (as suggested by the rusty posteruption surface waters pictured on the cover of this issue), they have been able to estimate the CO_2 and mineral contents of water throughout the lake. Based on this information, a two-phase eruption model was proposed by William Evans and Lloyd White (US Geological Survey, Menlo Park, California), Michelle Tuttle (USGS, Denver, Colorado), George Kling (Biology Department, University of Michigan) Gregory Tanyileke (Institute for Geological and Mining Research, Yaounde, Cameroon) and Robert Michel (USGS, Reston, Virginia).[1]

According to their model, the eruption began when an unspecified disturbance caused mixing across a chemocline at a depth of about 40 m in the lake. This phase of the eruption lasted for hours and was fairly quiet, because each liter of water involved yielded only about 2 to 3 liters of CO_2. As the eruption proceeded, however, water from successively deeper layers was forced up into the eruption column by turbulence, and the eruption became more vigorous. When the column penetrated the chemocline at about 150 meters, the short-lived, violent second phase of the eruption commenced. Because each liter of bottom water released 11 liters of CO_2 gas, this phase caused the highest fountaining and most of the physical damage.



EXIT VELOCITIES of CO_2–water jets calculated by Zhang's model, shown here as a function of the depth at which the water begins to degas (the saturation depth), serve as upper bounds on the actual velocity, because the calculation ignores factors such as turbulence and entrainment of water in the erupting column. Nonetheless, the calculation shows that a limnic eruption could easily account for the violence of the 1986 Lake Nyos eruption. (Adapted from ref. 3.)

Independently, Klaus Tietze of the German Federal Institute for Geosciences and Natural Resources in Hanover had also concluded that the eruption probably began at relatively shallow depths, and had arrived at a similar model.[2] Although these models accounted for most of the facts of the disaster at Lake Nyos, they could not explain several puzzling aspects of the eruption, such as how it started, why it ended even though plenty of CO_2 remained in the lake and why the eruption remained localized, rather than spreading throughout the lake.

Serendipitous seminar

These aspects also puzzled Youxue Zhang, a University of Michigan geologist, who attended a seminar on the Lake Nyos disaster given by Kling. Zhang, who had been conducting decompression experiments on CO_2-saturated water in an effort to understand the dynamics of gas exsolution as they relate to volcanism, saw the relation of his studies to the limnic eruption problem and began trying to model the process. His previous research had already made it clear that buoyancy causes more rapid ascent and degassing in water–CO_2 systems than is seen in magmas. He also realized that a steady-state eruption would require the pressure within the eruption conduit to be roughly equal to the hydrostatic pressure surrounding it. Using these insights,[3] Zhang developed an equation of state for the bubbly flow, used it to integrate the Bernoulli equation and found the exit velocity for a saturated CO_2–water mixture as a function of the depth at which degassing begins. (See the figure at left.) Zhang's calculation demonstrates convincingly that a limnic eruption can be both violent and localized, in accord with the details of the tragedies at Lake Nyos and Lake Monoun. More realistic calculations that include such effects as disequilibrium and the entrainment of shallow, unsaturated water within the eruption column may help explain why the eruptions stopped without completely degassing the lakes. Such calculations may also prove useful in efforts currently under way to tame the two lakes and render the fertile area around them safe for habitation.

Taming killer lakes

Although the limnic eruptions in Cameroon significantly decreased the CO_2 concentrations in the waters, they by no means rendered the lakes safe. The CO_2 in the bottom waters is increasing again, and mixing is still inhibited by density stratification of the lakes. Recent estimates suggest that Lakes Monoun and Nyos could both become dangerously unstable again, in 3–7 years and 20–36 years, respectively. Lake Nyos poses an additional hazard in that the natural dam of porous, volcanic tuff that holds in place the upper 40 m of lake water could give way, unleashing roughly 50 million cubic meters of water in a flood that would prove much more devastating than the 1986 eruption. These increasing hazards have led to calls for remediation in the form of shoring up the dam and controlled degassing of the lakes.

Currently, the leading proposal for degassing the lakes[2,4] is to run pipes into the lakes' bottom waters and begin pumping the CO_2-rich fluid toward the surface. Once the water begins to degas, the pump would be turned off, and a controlled limnic eruption within the pipes would shoot the CO_2–water mixture high into the air, possibly with velocities approaching those in Zhang's model. Calculations with improved models will be needed to determine the safety of such procedures before they can be carried out on a large scale. However, initial small-scale trials at Lake Monoun have indicated that the lake could be safely degassed over a period of a year using only two or three 141-mm diameter pipes. Lake Nyos, with 26.5 times as much dissolved CO_2 as Lake Monoun would require a correspondingly greater number of pipes—a fact that has led to the project being referred to as the "Lake Nyos organ pipes."

Another proposal is motivated by the observation that the CO_2 concentration in the bottom waters of Lake Nyos is now increasing much more rapidly than the concentration of dissolved solids. Evans and his collaborators argue that this observation may imply that a reservoir of gaseous CO_2 somewhere below the lake is the source of dissolved gas. If so, it may be possible to drill into the reservoir and cut off the flow of gas at its source.

A unique system?

The fact that the only known sites of limnic eruptions are located within 100 km of each other raises the question of whether other lakes may be susceptible to such catastrophic events. Anthropologist Eugenia Shanklin of Trenton State College in Trenton, New Jersey, has found some evidence of similar past events in the folklore of Cameroon's Northwest Province and plans to carry out more exhaustive studies in the near future.

Lake Mashu in Japan exhibits a buildup of CO_2 in its bottom waters during part of the year. However, winters in Japan are sufficiently severe that cold, dense surface water can mix across the chemocline on a yearly basis. No such yearly mixing occurs in the Cameroonian lakes, although Kling has pointed out that the eruptions of Lakes Nyos and Monoun both occurred during the cool rainy season, when a disturbance would be most likely to cause mixing.

A more threatening candidate lake is found near the refugee camps along the Zaire–Rwanda border. Lake Kivu—with an area of 2370 km^2, a maximum depth of over 485 m, over 700 times as much dissolved gas as is found in Lake Nyos and several active volcanoes on its floor—exhibits a stratified structure similar to that found in the two Cameroonian lakes. Although Lake Kivu is undoubtedly much more stable than Lakes Nyos and Monoun, procedures similar to those for degassing those lakes have already been used to commercially extract methane (and CO_2) from Lake Kivu's waters. (Tietze, who in 1981 proposed a scheme for tapping Lake Kivu's 6.3×10^{10} cubic meters of methane, estimates the reserves to be worth $20 billion.) Moreover, Kling notes that a 4000-year-old layer in a Lake Kivu sediment core has a high concentration of fish bones and debris from the lake shore, which may indicate the past occurrence of a limnic eruption at Lake Kivu. He adds, "If this were to happen today, at least a million people in the Kivu basin could be affected."

On the other hand, if Lakes Nyos and Monoun are the only two lakes in the world that experience limnic eruptions, one wonders what other surprises remain to be discovered in Cameroon's Northwest Province.

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Researchers Vie to Achieve a Quantum-Dot Laser

Believing that less is more, many researchers are trying to create quantum-dot, or zero-dimensional, lasers.

If semiconductor quantum-well lasers are so successful, shouldn't quantum-wire or quantum-dot lasers be even better? That's a question that many researchers have set out to answer. Quantum wells confine the charge carriers in one dimension; wires confine them in two; and dots, in three. (Quantum dots are clusters of semiconductor material with a few thousand atoms.) As a result of their confinement, the charge carriers occupy discrete energy levels similar to those of electrons in an atom.[1] Energy pumped into the system raises the charge carriers from one energy level to the next; none of it goes to random motion, because there are no other degrees of freedom. Thus, one expects any lasing from the dots to occur with high efficiency and at lower threshold current than in either quantum wells or quantum wires.

Since researchers in the early 1990s identified photoluminescence and electroluminescence coming from quantum dots, the study of these structures has become crowded and competitive. There have been claims of lasing, but they are often greeted with skepticism, because it is so difficult to establish that lasing comes from the dots and not some other source. At the Materials Research Society meeting in Boston last November, a group from Stuttgart presented additional evidence of lasing, and more reports are expected at meetings in the next few months.

Making dots

The minuscule clusters used in these studies are formed by using molecular beam epitaxy or chemical vapor deposition to lay one semiconductor material, such as indium gallium arsenide, on top of another substance, such as gallium arsenide, whose lattice constant differs from that of the overlayer by up to 8 percent. As the first few monolayers of InGaAs are laid down, the atoms arrange themselves in a two-dimensional layer, called the wetting layer. But as growth proceeds, it becomes three dimensional at a rather abrupt transition, with islands of InGaAs forming at various places scattered across the surface, connected by a wetting layer just a few atoms thick. The competition between the surface and interface tensions causes the atoms to bunch up in dots much as water molecules form beads on the hood of a freshly waxed car. Because the layers spontaneously generate islands, they are often referred to as self-assembled quantum dots. Once the InGaAs dots form, they are covered with another layer of GaAs, so that the island becomes embedded in a material with a wider bandgap, like a sandwich of different bandgap materials in a quantum well.

It was long known that islands would form as one grew highly strained semiconductor layers; in fact, materials scientists usually took steps to prevent it. But groups from the University of Southern California and from Bell Laboratories, Lucent Technologies (formerly AT&T Bell Labs), found in 1989 that if the islands are formed far from equilibrium, they are surprisingly free of defects.[2] The islands often look like tiny pyramids, whose bases are on the order of 10 nanometers across and whose heights are even less. Dot sizes depend on growth conditions and chemical composition, but their dimensions are often smaller than the de Broglie wavelength of thermal electrons. The exact diameter of the base varies from dot to dot by about 10–20% (the heights are more uniform).