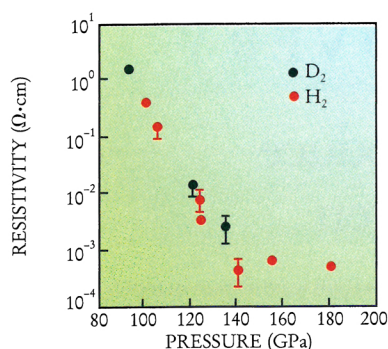




METALLIZATION of hydrogen (red) and deuterium (black) is evident from the leveling out of resistivity as a function of pressure and by the low measured resistivities, which are similar to those of some liquid metals at comparable temperatures.

Applications and future progress

For now, however, the discovery of metallic hydrogen under conditions of high temperature and relatively low

pressure will probably be most influential outside of high-pressure physics. According to Nellis, the Livermore shockwave experiments measure the density dependence of the bandgap under conditions similar to those in the initial stages of fuel-pellet irradiation in laser fusion. These data show that electronic excitations of the fuel pellet's hydrogen absorb more energy than was thought previously. Because energy absorbed by electronic excitations does not heat the fuel, this implies higher compressibility and higher laser-fusion yields than expected.

The results also have important implications well beyond the laboratory. According to Caltech planetary physicist David Stevenson, they are particularly welcome among planetary physicists trying to account for the high magnetic fields of hydrogen-rich giants Jupiter and Saturn. The onset of metallization at lower-than-expected pressures implies that the dynamos generating the magnetic fields are located much closer to the surface than previously thought. Because the roughly

dipole magnetic field generated by the dynamo decays approximately as the inverse cube of distance, a near-surface dynamo need not generate unreasonably large fields. Similar considerations probably also apply for the planets recently discovered orbiting the stars 51 Pegasi, 70 Virginis and 47 Ursae Majoris, although the nearness of these planets to their respective stars places them in another temperature regime. (See *PHYSICS TODAY*, March, page 9.)

In future shockwave experiments, Weir, Mitchell and Nellis hope to probe such higher temperature conditions, as well as to continue checking their results by using different anvil and sample materials. Given their recent findings, one looks forward to what they may achieve as an encore.

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Measuring Distances to More Supernovae Sharpens the Hubble Constant Debate

A recent *Astrophysical Journal* letter by veteran astronomer Allan Sandage (Carnegie Observatories, Pasadena, California) and coworkers¹ offers some solace to troubled adherents of the cosmological scenario most favored by the theorists. The contentious observational issue is the value of H_0 , the Hubble constant. A variety of measurement schemes that use properties of galaxies have in recent years put H_0 between 80 and 85 km/s per megaparsec. (A megaparsec is 3.3 million light-years or 3.1×10^{19} km.) But Sandage and company, using supernovae, have long held out for a value closer to 50 km/(s·Mpc). "Our new paper," Sandage contends, "is the beginning of the end of the Hubble-constant wars."

Other groups that also use supernovae question Sandage's finality and argue that he somewhat underestimates H_0 . But like him, they also find H_0 to be well below 80 km/(s·Mpc). This troubling discrepancy between two different but equally respectable classes of techniques remains, in the opinion of most of the cognoscenti, a puzzle still to be resolved.

The stakes are high. In the general cosmic expansion, the recessional velocity of any sufficiently distant galaxy is proportional to its distance from the observer. H_0 is the proportionality constant. The total elapsed time since the

Measuring the Hubble constant with supernovae continues to suggest an older universe than one gets with other yardsticks.

Big Bang is given by H_0^{-1} times a theory-dependent constant of order 1. The favored inflationary Big Bang scenario, for example, gives $\frac{2}{3}H_0^{-1}$ for the age of the universe.

But the existence of some very old stars in our own Galaxy imposes a severe limit on the theorists' freedom to play with the age of the universe. The oldest globular star clusters in the Milky Way are, at the very least, 12 billion years old.² It becomes embarrassing to adhere to a cosmology that makes the universe younger than our local globular clusters. Inflationary Big Bang cosmology, or any other scenario with critical closure mass density, requires that H_0 be no larger than about 54 km/(s·Mpc), if the universe is to be older than 12 billion years. If H_0 turns out to be bigger than about 80 km/(s·Mpc), no Big Bang scenario yields an age greater than 12 billion years unless it invokes a nonvanishing "cosmological constant"—a kind of universal repulsion that would work against gravity.

Standard supernova bombs

The new paper by Sandage *et al.*¹ re-

ports an H_0 of 57 ± 4 , just barely consistent with Big Bang theories with the desired critical closure density and vanishing cosmological constant. To measure the Hubble constant, one needs a collection of cosmologically distant objects for each of which one knows both the recessional redshift and, independently, the distance. To that end, the Sandage group avails itself of type Ia supernovae, whose distinguishing signature is the absence of hydrogen in their spectra. The intrinsic luminosity of type Ia supernovae at peak brightness, a few days after the explosion, is thought to vary relatively little from case to case. That's because they are all believed to be exhausted white dwarfs that accrete additional mass from a partner until they suddenly blow up somewhere near the so-called Chandrasekhar limit—about 1.4 solar masses. Just how much variation there is within the type Ia class, and what one needs to do about it, is a subject of voluble contention between Sandage and other groups seeking to determine the Hubble constant by means of supernovae. In any case, type II supernovae, with a considerable range of ignition masses and residual cores, exhibit a much greater variation of intrinsic luminosities than the type Ia's.

To the extent that type Ia supernovae

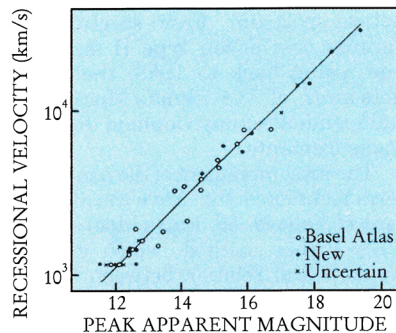
vae really are “standard bombs,” as Sandage calls them, one can immediately determine their distances from their apparent luminosities, *if* one knows the unique intrinsic peak luminosity of the class. Five years ago, Sandage and coworkers began using the newly launched Hubble Space Telescope to determine this intrinsic luminosity and demonstrate how little it varies from one type Ia explosion to the next. (See PHYSICS TODAY November 1992, page 17.)

The plan was to measure the light curves of Cepheid variable stars in several relatively nearby galaxies in which type Ia supernovae have been measured. The dates of these local supernovae range from 1990 all the way back to 1895. A Cepheid variable is a wonderful yardstick. Its brightness varies regularly with a period of days or weeks. The mean intrinsic luminosity of a Cepheid is simply determined by its period; the longer the period, the more luminous the star. Therefore, to know the distance of a Cepheid variable star, one has only to measure its period and apparent brightness. The more Cepheids one can measure in a galaxy, the better one can determine its distance from us.

The great hope was that the Hubble telescope could measure Cepheids in galaxies as far away as 25 megaparsecs, far beyond anything one could do with Earthbound telescopes. One has to go out as far as possible, because nearby supernova explosions are quite rare. Within a radius of 25 Mpc, less than a dozen type Ia supernovae have been recorded in this century. Supernovae are easy to see at more than ten times that distance; that's what makes them such desirable probes of the distant cosmos. But a new type Ia supernova close enough to calibrate by means of Cepheids in the same galaxy comes along only once or twice a decade, even in the age of the Hubble telescope.

Before and after

Before the flawed Hubble telescope was refitted with corrective optics at the end of 1993, Sandage's group was able to determine Cepheid distances to only two galaxies that had hosted historical type Ia supernovae. The farther one was only 5 Mpc away. With the flawed Hubble optics, acquiring good Cepheid light curves at even so modest a distance was admired as a *tour de force* for group member Abhijit Saha (Space Telescope Science Institute, Baltimore). Now that the Hubble telescope has been taking miraculously sharp pictures for more than two years through the corrective optics of its second-generation Wide Field Planetary



HUBBLE DIAGRAM of distant type-Ia supernovae used by Sandage *et al.*¹ to determine the Hubble constant. Redshift velocity is plotted against peak apparent magnitude, a decreasing logarithmic measure of observed maximum brightness. If all the supernovae have the same intrinsic peak luminosity, all the points should lie, within errors, on the fitted straight line. And if one knows that intrinsic luminosity, the line's intercept gives the Hubble constant. (The slope is fixed by the definition of magnitude.) The newest supernovae (solid dots) were measured in recent years at the Cerro Tololo Inter-American Observatory. The other data points are from older sources.

Camera, Saha has measured the Cepheid distances to three more galaxies with historical type Ia supernovae, the farthest being 25 Mpc away. Availing themselves of an additional Cepheid distance measured by another group, Sandage and company have now calibrated the intrinsic peak luminosities of seven historical type Ia supernovae.

For this sample of seven relatively nearby supernovae the group reports an average peak absolute luminosity and an rms deviation.¹ The mean peak luminosity comes out to about 10 billion times that of the Sun, with a spread of only 18 percent. Sandage regards this modest spread among the seven calibrated explosions as a vindication of his treatment of type Ia supernovae as standard bombs.

This “near sample” of seven supernovae, of course, is used only to calibrate the intrinsic luminosities of the “far sample” of much more distant type Ia supernovae from whose galactic redshifts the Hubble constant is ultimately determined. The recessional velocities of objects as close as a mere 25 Mpc are presumed to be significantly distorted by flows toward large local mass concentrations such as the Virgo cluster of galaxies.

For type Ia supernovae well beyond

the reach of such local obfuscation, the “Hubble diagram,” a logarithmic plot of host-galaxy redshift against *apparent* peak brightness, should be a perfect straight line within measurement errors, to the extent that these supernovae all have the same intrinsic peak luminosity. (See the figure at left.) Once one has calibrated that intrinsic luminosity, the intercept of the Hubble line immediately gives H_0 . (The slope of this line is fixed at $1/5$ by the logarithmic definition of astronomical magnitude.)

Gustav Tammann (University of Basel), the Sandage group's supernova archivist, now has at his disposal 13 brand-new type Ia supernovae out to about 500 Mpc, recently discovered and measured by Mark Phillips and colleagues at the Cerro Tololo Inter-American Observatory in the Chilean Andes. With these very distant new additions to Tammann's comprehensive Hubble diagram for all the known type Ia supernovae beyond about 60 Mpc, the Sandage group gets its value of 57 ± 4 for the Hubble constant by positing that all the far supernovae have the same unique intrinsic peak luminosity as the Cepheid-calibrated near sample.

Critique

It is well known that type Ia supernovae do not, in fact, all have the same peak luminosity. Sandage and company excluded from their sample spectroscopically abnormal type Ia's of a kind that are known to be underluminous. But even for spectroscopically normal ones, Phillips and his colleagues presented evidence in 1993 for a monotonic correlation between peak luminosity and decay rate after the peak; the brighter ones decay more slowly. The Sandage group responded by culling from consideration supernovae with decay rates far from the mean. But in any case, Sandage argues, the difference in decay rates between the near and far samples is so small that correcting for it would produce, at worst, a 4 percent increase in H_0 .

But the Cerro Tololo group has developed a phenomenological technique for estimating the departure of any individual type Ia supernova's intrinsic luminosity from the class average by analyzing its temporal light curve.³ Robert Kirshner and colleagues at Harvard, borrowing the Cerro Tololo light curves, have developed a similar corrective to Sandage's strict standard-bomb prescription.⁴ Both groups, when they apply their corrections to the distant type Ia supernovae on the Hubble diagram and to the Sandage group's calibration sample, come up with an H_0 of about 64 km/(s·Mpc).

But first both of these groups had

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

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.

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.

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