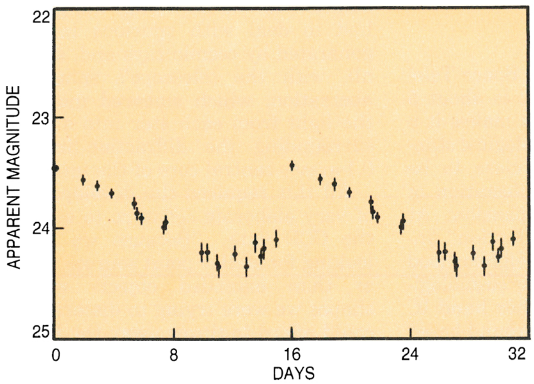
SUPERNOVA DISTANCE MEASUREMENTS SUGGEST AN OLDER, LARGER UNIVERSE

The Hubble constant, the conversion factor that translates the recessional velocities of remote galaxies into distances, is the only fundamental parameter of cosmology that astronomers think they know to within a factor of two. In the 1970s H_0 was thought to be somewhere around 50 km/sec per megaparsec. (A megaparsec is 3.3 million light years.) Then in the next decade, measurements of H_0 seemed to be converging on 80 or 90 km/sec-Mpc. But in just the last few months, three novel determinations[1,2,3] of H_0 based on the observation of supernovae have placed the Hubble constant back down in the regime 50–60 km/sec-Mpc.



Light curve data for a Cepheid variable star with a period of 16 days. This is one of 27 Cepheids in a galaxy 5 megaparsecs away that were measured with the Hubble Telescope.[1] The distance is determined from the well-known relation between the period of a Cepheid and its luminosity.

The stakes are high. H_0^{-1}, which has the units of a time, is the first approximation to the age of the universe. An H_0 as high as 85 km/sec-Mpc would require a nonvanishing cosmological constant λ in the equations of general relativity. An H_0 of 60 would not, *provided that* ρ, the mean matter density of the universe, is much smaller than its critical "closure" value ρ_c. A positive λ describes a universal repulsion that works against gravitation. Most cosmologists want λ to be precisely zero, but the observational limits are still very loose. (See PHYSICS TODAY, May 1987. page 17.) An H_0 as low as 45 km/sec-Mpc would let λ vanish even if $\rho = \rho_c$.

The important cosmological parameter Ω is the density ratio ρ/ρ_c. The widely accepted inflationary scenario of cosmic evolution requires that $\Omega = 1$, or at least that $\Omega + \lambda = 1$. But the matter astronomers can see directly or infer from the dynamics of galaxies would account for only about 10% of $\Omega = 1$. Hence the fevered search for "dark matter." (See Anthony Tyson's article in PHYSICS TODAY, June 1992, page 24.) The age of the globular clusters in our Galaxy, the oldest stars we know about, imposes a constraint on Ω and H_0. The larger Ω is for a given H_0, the smaller is the age of the universe. If an $\Omega = 1$ universe is to be old enough to accommodate the 14-billion-year-old globular clusters,[4] H_0 cannot be much larger than 50 km/sec-Mpc.

Supernovae of type Ia

To measure the Hubble constant one needs to compare redshifts of very distant objects with independent determinations of their distances. Astronomers are always on the lookout for "standard candles," classes of celestial objects all having the same intrinsic luminosity, because the ratio of their apparent luminosities immediately gives the ratio of their distances. It is widely believed that supernovae of type Ia could serve as standard candles at cosmological distances. These brightest of all supernovae appear to be "exquisite standard bombs, all made in the same workshop," asserts Allan Sandage (Observatories of the Carnegie Institution, Pasadena, California). In what many regard as a *tour de force* for the impaired Hubble Space Telescope, Sandage and his colleagues have recently succeeded in using it to measure the distance to the galaxy in which Fritz Zwicky found the prototypical type-Ia supernova in 1937.

Supernovae of type Ia, distinguished primarily by the lack of hydrogen in their spectra, are thought to manifest the explosive disintegration of white dwarf stars that had been quiescent because all their nuclear fuel had already been burned to carbon and oxygen—the end of the line for a star of less than 1.4 solar masses, the so-called Chandrasekhar limit. But if such an exhausted white dwarf has a binary partner from which it can gradually suck up additional mass, it would suddenly reignite if it came close enough to the Chandrasekhar limit. The resulting explosion would completely obliterate the star, leaving no residual core behind. This scenario implies that the intrinsic luminosity of a type-Ia supernova at maximum brightness (a few weeks after the explosion) varies very little, if at all, from one case to the next.

Standard candles of a given class are of little use until their intrinsic brightness is known. After that, one can determine the distance to any one exemplar simply by measuring its apparent brightness. Conversely, one can determine the absolute brightness of a class of standard candles by measuring the distance to any one exemplar. It was for the purpose of determining the intrinsic brightness of the type-Ia supernovae that Sandage and his collaborators undertook to measure the distance to IC 4182, the irregular dwarf spiral galaxy that housed the 1937 supernova.

Because spiral galaxies like IC 4182 have many young stars, they are expected to have Cepheid variable stars. Cepheids exhibit cyclic variations of brightness with periods on the order of days or weeks. There is a universal, well-calibrated relation between the period of a Cepheid and its mean intrinsic brightness. Therefore these variable stars serve as invaluable distance indicators to galaxies close enough for astronomers to measure their Cepheids.

The Space Telescope

That's where the Hubble Space Telescope comes in. IC 4182 is about 5 megaparsecs away. That makes it a neighbor of ours by cosmological standards. It is much too close to be studied as a direct manifestation of the universal Hubble expansion. At such distances, "pecular motion" under the influence of neighborhood galaxies is comparable to cosmological recession. On the other hand IC 4182 is too far away for ground-based telescopes to see more than one or two of its very brightest Cepheids, and making even marginal light-cycle measurements from the ground would require inordinate exposure times.

But there isn't much choice. Supernovae of all types are quite rare. Galaxies like our own have only one or two supernovae of type Ia per millennium. In fact, IC 4182 is just about the closest galaxy that has Cepheids *and* a well-measured historical supernova of type Ia.

With the launching of the Hubble telescope in 1990, astronomers finally had an instrument that should be able to determine the absolute brightness of a type-Ia supernova by adequately measuring its surviving Cepheid neighbors. But not long after it was launched, the world learned that the Hubble's optical system was seriously impaired. (See PHYSICS TODAY, August 1990, page 17.) So it was with particular admiration and some relief that astromomers who had assembled in Sardinia this summer to hear new Space Telescope results saw 27 very well-measured light curves from Cepheid variable stars in IC 4182. (See the figure on page 17.) These data were presented by Sandage's collaborator Nino Panagia, from the Space Telescope Science Institute in Baltimore. The other collaborators were Abhijit Saha and Duccio Macchetto from STScI, and the University of Basel's Gustav Tammann, Sandage's old comrade in the battle for a smaller Hubble constant.

The observations were carried out with the Hubble's Wide Field and Planetary Camera over a 47-day period early this year. The camera's square field of view, $2\frac{1}{2}$ arcminutes on a side, is covered by an array of 1600×1600 CCD pixels. IC 4182 is about 4 arcminutes wide. The search for Cepheids was concentrated on the quadrant of the galaxy where the supernova had been seen 55 years earlier. The five thousand or so resolvable stars in this quadrant make for a very crowded field. In addition to the crowding, the group had to deal with spurious images generated by cosmic rays and, above all, with the telescope's spherical aberration, which smeared most of the light from each star into a halo surrounding the diffraction-limited 0.1-arcsec central core of the image.

All this required the development of very elaborate software to search the CCD data. "Because we were looking for stellar point sources rather than extended objects whose shapes we were trying to discern, we could afford to throw away the halos and all their noise," Saha told us. "All the signal-to-noise is in the cores." The 27 Cepheids, with periods ranging from four days to six weeks, were found by comparing exposures at different times and looking for cyclic variations. All the imaging was done in the wavelength interval 5000–6000 Å.

Plotting the periods of these 27 variable stars against apparent magnitude m (averaged over a cycle) shows the expected clustering around the well-known Cepheid period–luminosity line, whose calibration in *absolute* magnitude M has been determined by many measurements of Cepheids at known distances in our own Galaxy. Because M and m are logarithmic measures of intrinsic and observed luminosity, respectively, the difference $m-M$, the so-called distance modulus, will be the same for all objects at a given distance from us. In particular, the 1937 supernova should have had the same distance modulus as these 27 Cepheids measured by the Hubble telescope. Thus the best fit of the period–luminosity line to the 27 Cepheids immediately lets one translate the 1937 supernova data into an absolute magnitude.

The distance modulus thus measured tells us that IC 4182 is 4.94 ± 0.11 Mpc away and that the absolute magnitude of the 1937 supernova at maximum brightness was -19.76 ± 0.13. That's 10^{10} times the intrinsic luminosity of the Sun, albeit a flash in the pan. (By convention, the brighter the object, the more negative the magnitude.) The possibility that intragalactic dust in IC 4182 may have absorbed some of the light from the supernova and the Cepheids has less effect on the supernova brightness calibration than on the distance determination: Dust obscuration would make the Cepheids seem farther away than they really are. But if the supernova light was dimmed by the same percentage, the exaggerated distance determination would jack up the calculation of its intrinsic luminosity just enough to compensate for the dimming. In any case, auxiliary measurements in the near-infrared have convinced Sandage and company that the amount of obscuring dust in IC 4182 is negligible.

The Hubble diagram

For any object far enough away that we can neglect its peculiar local motion, the Hubble law of universal expansion asserts that $D=v/H_0$, where D is its distance from us and v is its recessional velocity. If type-Ia supernovae are perfect standard candles, the Hubble law tells us that plotting $\log v$ (as determined from Doppler redshifts) against apparent magnitude m at maximum brightness for all sufficiently distant type-Ia supernovae should yield a straight line whose intercept depends only on the value of H_0 and the absolute magnitude of the class of type-Ia supernovae.

Various astronomers have compiled such Hubble diagrams for dozens of type-Ia supernovae whose recessional velocities exceed 1000 km/sec. (See the figure in page 19.) The data points do exhibit some scatter around the expected Hubble line, which might be indicative of considerable dispersion in the intrinsic brightness of type-Ia supernovae. But Tammann, the group's acknowledged supernova expert, argues that the observed scatter is entirely consistent with observational uncertainties and *zero* intrinsic dispersion.

Assuming their own measurement of the absolute magnitude of the 1937 supernova to be valid for all type-Ia supernovae, and taking the best value of the Hubble diagram intercept from the various extant compilations of the more distant supernovae, Sandage and his colleagues arrived at 45 ± 9 km/sec-Mpc as their best estimate of H_0. That's what they reported in Sardinia.

But the story has a nice final twist. Because the existing Hubble diagrams of the distant type-Ia supernovae had all been compiled from data in the "blue" window (4000–5000 Å), the best linear fit to these diagrams had to be converted to the "visible" window (5000–6000 Å) before it could be put together with the Cepheid measurements in the visible to yield H_0. This conversion required a judgment as to just how blue supernovae of type Ia really are. Given the variety of dust conditions in all those distant galaxies, that's not an easy question.

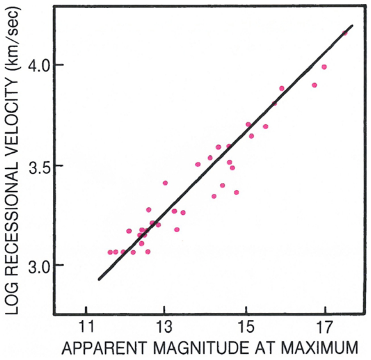
After studying the preprint detailing the results presented by Panagia in Sardinia, David Branch, a supernova specialist at the University of Oklahoma, concluded that Panagia and his colleagues had used a color index for the type-Ia supernovae that was too blue. After an extensive discussion with Branch, Tammann decided that the best course was simply to redo the Hubble diagram in the visible by digging the longer-wavelength data from 42 historic type-Ia supernovae out of the imposing catalog he has compiled over the years. The Hubble diagram on this page is the result of that impressive exercise in astronomical archaeology. One might well ask whether it would not have been easier to measure the IC 4182 Cepheids in the blue to begin with. The answer is that CCDs tend to be much less sensitive in the blue than at the longer wavelengths.

Having completed his new 5000–6000-Å Hubble diagram in September, Tammann recalculated the Hubble constant. The best estimate of H_0 based on the IC 4182 Cepheids had gone up to 51 ± 9 km/sec-Mpc. The group's paper, which will appear next month in *Astrophysical Journal Letters*,[1] has a note added in proof giving the new, higher value for H_0.

Weighing the nickel

This readjusted estimate of H_0 brings the Sandage group's result into excellent agreement with Branch's own recent estimate of the Hubble constant.[2] Branch also exploits type-Ia supernovae as standard candles, but he arrives at their intrinsic brightness by a quite different route: His principal concern is to estimate the total mass of nickel-56 produced by the burning of the carbon and oxygen that make up a white dwarf near the Chandrasekhar limit.

A rapid chain of fusion reactions in the supernova explosion has the net effect of combining two carbon nuclei with two oxygens to form a nucleus of ^{56}Ni, the most tightly bound nucleus one can get with equal numbers of protons and neutrons. Every gram of



Hubble diagram of log velocity vs apparent magnitude at 5000–6000 Å, compiled by Gustav Tammann from the records of 35 type-Ia supernovae with recessional velocities above 1000 km/sec. The straight line is the best fit to Hubble's law, assuming they all had the same intrinsic luminosity. Because magnitude goes like $-\frac{5}{2}$ times the log of luminosity, the slope is fixed at $\frac{1}{5}$. The intercept depends only on the intrinsic luminosity and H_0.

nickel thus synthesized contributes 7.8×10^{10} joules of nuclear energy to the supernova explosion. The total kinetic energy of the explosion products equals the total nuclear energy released in the fusion reactions minus the gravitational binding energy of a white dwarf approaching the Chandrasekhar limit.

Over the next several months all that nickel decays to iron-56, the most tightly bound nucleus of all, by a leisurely sequence of beta decays. The radioactivity of the nickel is what heats up the surrounding gases and thus generates the light by which we see a type-Ia supernova.

To calculate the peak luminosity from this scenario, Branch avails himself of numerous observational inputs and detailed model calculations in the recent literature. He estimates the total mass of nickel from the kinetic energy of the explosion, as measured by Doppler blueshifting of spectral lines from the expanding gas, and from the spectroscopic detection of intermediate fusion products. The burning, Branch concludes, produces about 0.6 solar masses of nickel.

An important observational input is the time t_{max} that elaspes between the explosion of a type-Ia supernova and its peak luminosity. Unfortunately supernovae are usually well under way before they are noticed, so this interval is not known very well. From a survey of published light curves, Branch estimates t_{max} to be 19 ± 2 days. From t_{max}, the nickel mass and a parameter α that summarizes the results of detailed radiation-transport models, Branch arrives at a peak absolute magnitude of -19.61 ± 0.35 in the blue wavelength window. Applying this absolute magnitude to a Hubble diagram of 35 distant type-Ia supernovae, he finally arrives at 56 ± 10 km/sec-Mpc for the Hubble constant, in good agreement with Sandage and company.

Five months ago the agreement wasn't quite as good. Not only was Sandage's estimate of H_0 12% lower back then; Branch's was 9% higher. In his *Astrophysical Journal* article[2] that appeared just before the Sardinia conference, Branch had estimated the Hubble constant at 61 ± 10 km/sec-Mpc. But in recent weeks, he told us, an important new radiation-transport calculation[5] by Aleksei Khokhlov and his colleagues at the Max Planck Institute for Astrophysics in Garching, near Munich, has increased the best estimate of α by 16%. "It's the first of these model calculations to use realistic opacities," Branch told us, "so we have to take it seriously." The result is higher intrinsic luminosity and thus the somewhat smaller H_0.

Type-II supernovae

Type-II supernovae are certainly not standard candles. Their physics involved no characteristic mass like the Chandrasekhar limit. Nonetheless, Brian Schmidt, Robert Kirshner and Ronald Eastman at the Harvard–Smithsonian Center for Astrophysics have recently demonstrated[3] that one can exploit these explosions of red or blue giants to measure H_0. Despite the fact that those giant stars are at least six times as massive as the white dwarfs, their explosions are less luminous than the type-Ia supernovae because 99% of the energy comes out in a burst of neutrinos.

The spectacular supernova of 1987, the first one visible to the naked eye in almost four centuries, was a type-II. As the most exhaustively measured supernova in history, SN 1987A has provided indispensable guidance and confirmation for the detailed model calculations required by the Harvard group's method. But as a cautionary note one should point out that SN 1987A was atypically weak by type-II standards. It was so spectacular only because it was so close.

To circumvent the touchy issue of standard candles, Kirshner and his colleagues have devised a means of measuring the distances to individual type-II supernovae as far away as 200 Mpc. With these distances in hand, the corresponding measured recessional redshifts yield a straightforward determination of H_0. There's no need to posit a universal intrinsic luminosity. The Harvard group has thus far made distance estimates from the records of ten extragalactic type-II supernovae going back as far as 1968.

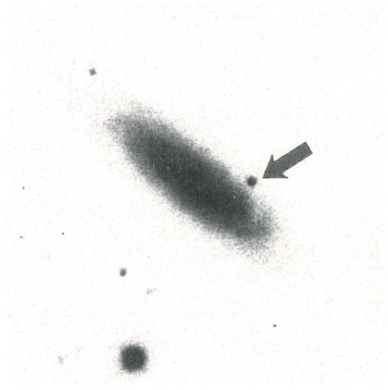
When the core of a red or blue giant suddenly collapses after the exhaustion of its nuclear fuel, its rebound sends a shock wave out through the star, disrupting the surface and accelerating its gases to relativistic speeds. From spectroscopic records of the free expansion of the glowing surface gases during the weeks following the initiating core collapse, the Harvard group extracts the temperature and velocity of the expanding surface as a function of time. The color of the continuum radiation gives the temperature, and the Doppler blueshifts of the hydrogen lines give the expansion velocity.

If the expanding hot gas were a perfect blackbody, these data, together with a simple measurement of the radiant flux reaching the Earth, would suffice to determine the distance to the supernova: From Planck's radiation law, the surface temperature tells us the radiant output per unit surface of the expanding photosphere, and the velocity profile records the growth of its total area. That gives the total radiant output of the supernova at a given time, and we have only to compare it with the flux reaching us to know the distance.

The real situation is more complicated, and that's where the elaborate computer modeling comes in. The type-II supernovae are, in effect, "dilute blackbodies." The *shape* of the continuum spectrum follows the Planck function, but the normalization is reduced by scattering and absorption of the radiation in the stellar interior. The Harvard group's computer model, constrained particularly by the data from SN 1987A, shows that the extremely complicated interactions with the supernova gases can be embodied in a single correction factor to the Planck blackbody formula that depends only on temperature.

The nearest of the ten type-II supernovae thus measured by the Harvard group is SN 1987A. It's only 50 kpc away, in the Large Magellanic Cloud next door to the Milky Way. Therefore it's of no interest for determining H_0. But because the distance to the LMC has been measured well by half a dozen other methods, it serves as a good check on the "expanding-photosphere method."

From the redshifts and distances of the other nine type-II supernovae, going all the way out to 120 Mpc, the Harvard group gets a best fit of 60 ± 10 for H_0. The quoted uncertainty would be significantly smaller, Kirshner told us, but for the fact that the most distant of the nine yielded a particularly fuzzy distance measurement, for reasons that have nothing to do with its remoteness. Kirshner is convinced that the expanding-photosphere method will provide good distance measurements to type-II supernovae considerably beyond 120 Mpc.



Very distant type-II supernova (arrow) imaged in 1990 by CCDs on the 2.1-meter telescope on Kitt Peak. The adjacent large oval is its nameless parent galaxy. Their common recessional velocity is 7700 km/sec. The supernova's distance from us, as determined by the expanding-photosphere method,[3] is 117 ± 20 megaparsecs. That makes it by far the most distant supernova for which we have a direct distance measurement independent of redshift.

The more distant the supernova, the better its measurement will constrain the Hubble constant—so long as one doesn't go so far out that one begins to see the effects of cosmic deceleration. In fact, a British–American collaboration by led Saul Perlmutter, Carl Pennypacker and Gerson Goldhaber at Berkeley has undertaken to measure the slowing down of the Hubble expansion by systematically searching for extremely distant supernovae. Last month they reported that they had found the most distant supernova ever seen—a type-Ia with a fractional redshift of 0.46, implying a distance in excess if 1.5 *giga*parsecs.[6]

Confrontation

So we have three independent means of exploiting supernovae to determine the Hubble constant; and all three cluster nicely around 55 km/sec-Mpc. That's a long way from the region around 85 km/sec-Mpc favored by the techniques that have been popular for a decade. They measure various properties of distant galaxies. Chief among these is the Tully–Fisher method, which invokes an empirical relation between the rotational velocities of galaxies (as measured by Doppler line broadening) and their intrinsic luminosities. "Either the higher values of H_0 are wrong," says Sandage, "or we're wrong. We don't really know yet whether the type-Ia supernovae are good standard candles. But we'll know better when we've measured a few more."

Next year Sandage and his colleagues hope to measure Cepheids in another relatively nearby galaxy in which a type-Ia supernova has been recorded. Some time around the end of 1993 the Space Telescope is scheduled for a visit from astronauts bearing corrective optics. After that the telescope should be able to measure Cepheids as far away as 25 Mpc.

Sandage and Tammann have been arguing for years that techniques like Tully–Fisher overestimate the Hubble constant because of an insidious statistical effect called Malmquist bias. The Swedish astronomer Gunnar Malmquist warned his colleagues against it in the 1930s. As Sandage explains it, Malmquist pointed out that one finds ever more extreme cases as one enlarges the volume of search. The larger the school, for example, the taller is the tallest pupil likely to be. Applying this general caveat to Tully–Fisher, Sandage suggests that the use of ever more distant galaxies skews the sample in favor of atypically luminous galaxies for any given rotation rate. The best way to free oneself from Malmquist bias, Sandage suggests, is to seek out phenomena that have negligible intrinsic dispersion.

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