

Testing Dark Energy

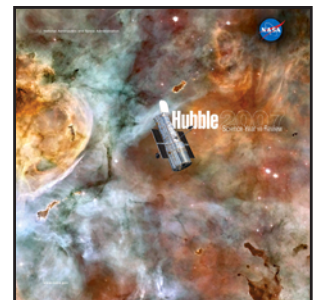
Adam Riess

Taken from: Hubble 2007: Science Year in Review

Produced by NASA Goddard Space Flight Center and Space Telescope Science Institute.

The full contents of this book include more Hubble science articles, an overview of the telescope, and more. The complete volume and its component sections are available for download online at:

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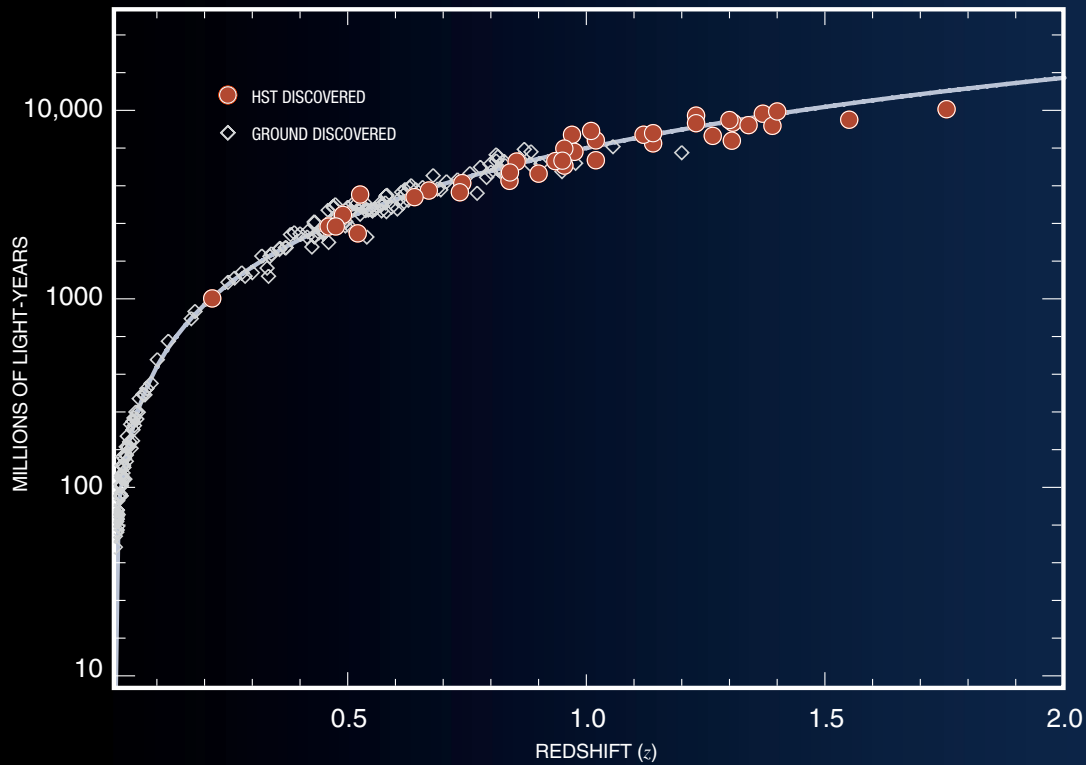
As Odysseus's ship passed through the strait, he was threatened by Charybdis, the whirlpool to starboard, and Scylla, the monster to port. He could not avoid them both, so one of them would determine his destiny. We now see the fate of the universe caught in a similar epic struggle between two powerful forces—normal gravity and a newly found component called “dark energy” are vying for control of the universe. Gravitational attraction could collapse the universe to a dot, or the repulsion of dark energy could blast it apart. Today, our best evidence says that repulsion is beating attraction, and the universe will expand forever. With cosmic destiny at stake, however, it is worth testing the evidence from every angle!

Remarkably, astronomers only became aware of this grand tug-of-war in the last decade. Previously, it was thought that the attraction of gravity was unopposed. In that case, the gravitational force pulling on all the matter should have slowed down the expansion of the universe during the 13.7 billion years since the Big Bang. However, observations published by the author with the High- z Team in 1998 and those reported in 1999 by the Supernova Cosmology Project revealed different—and astonishing—results for the expansion rate. The observations said that cosmic expansion for at least the last 5 billion years has been *speeding up*, not slowing down. This was an enormous surprise!

To measure the expansion rate of the universe, we searched for a special kind of exploding star—Type Ia supernovas—which can rarely and randomly appear in any galaxy. We can determine the distance to a Type Ia supernova from its brightness (see sidebar), and then we can calculate the travel time of light from there to here by dividing the distance by the speed of light, which is a universal constant. Separately, we determine the factor by which the universe expanded during the journey of the light from the Type Ia supernova and its host galaxy. To determine this factor, we measure the star's spectral redshift. (See the sidebar “Cosmological redshift, cosmic time, and distance” in the accompanying article by Scoville.) After observing many Type Ia supernovas spread over cosmic time, we can reconstruct the expansion history of the universe.

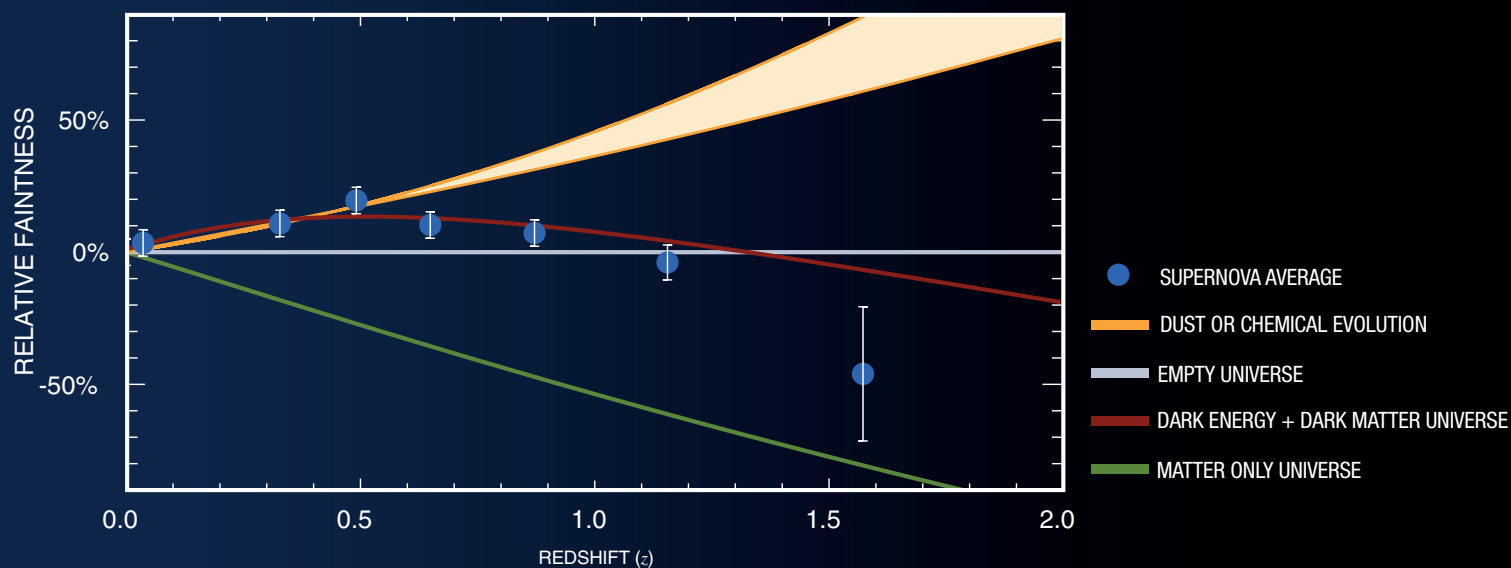


NGC 1309, a beautiful spiral galaxy, hosted a Type Ia supernova in 2002 (see image on page 116).



Measurements of the distances and redshifts of Type Ia supernovas, acquired either by *Hubble* or ground-based telescopes, that reveal a historical variation in the expansion rate of the universe. The solid curve is the best fit to the observed data points.

Recent *Hubble* observations of distant supernovas indicate that the expansion of the universe was decelerating for the first 8 billion years of cosmic history, before it began accelerating approximately 5–6 billion years ago. Astronomers found that Type Ia supernovas with redshifts greater than 1 were brighter than they would expect if intergalactic dust or chemical evolution were continuously dimming the supernovas' light and contaminating the measurements of their distances, including the relatively nearby supernovas at redshifts about 0.5 that first pointed to the existence of dark energy.



A plot of supernova data viewed against various theoretical models. Each blue point is an average of numerous Type Ia supernovas, all observed at about the same redshift. It can be seen that the data best fit a universe composed of a mixture of dark matter and dark energy. The evidence is the excessive distance (apparent faintness) of Type Ia supernovas in the recent past (redshift about 0.5). This implies that the universe has recently been undergoing accelerating expansion. If dust or chemical evolution had caused this faintness, it would have been greater in the more distant past (redshift greater than 1). However, observations from *Hubble* rule out this possibility and show that the expansion was slowing, due to braking by the gravitational force of dark matter, before it began speeding up. The graph is normalized to an “empty universe” line, which mathematically represents an expanding universe neither slowed by the presence of gravitational matter, nor accelerated by dark energy.

Our basic evidence for accelerated expansion is that certain Type Ia supernovas were fainter—and therefore, apparently farther away—than they should be if the expansion rate were constant or slowing down. The straightforward explanation for this observation is that the expansion rate of the universe is now accelerating. If true, and if this behavior began only relatively recently in cosmic history as the data indicates, then Einstein might be forgiven for what he called his “biggest blunder.” His General Theory of Relativity, published in 1915–16, predicted that the universe should either be expanding or contracting. Convinced that it couldn’t be expanding, he inserted a mathematical antigravity term (now called the cosmological constant) to counter the case of the possible contraction of the universe, because observations at the time showed the cosmos to be static. A decade later, when better observations by Edwin Hubble convincingly demonstrated that the universe

Type Ia Supernovas—The Workhorses of Cosmology

The Type Ia supernova is the workhorse of observational cosmology. (Cosmology is the investigation of the nature and origins of the universe.) In its sudden brilliance, a typical Type Ia supernova puts out 4 billion times as much light as our Sun, making it briefly visible far across space. What makes these massive explosions truly *useful* is the fact that their intrinsic brightness is known and understood. This calibration qualifies a Type Ia supernova as a “standard candle.” That is, knowing the intrinsic brightness beforehand, we can compute the distance to any Type Ia supernova by applying the inverse-square law of brightness. For example, at twice the distance, a standard candle appears one-quarter as bright.

The precursor of a Type Ia supernova is actually one of two orbiting stars bound by gravity. The one that is destined to explode began life as an ordinary star, with mass similar to the Sun or smaller. After burning up its nuclear fuel, it collapsed to a bright cinder of completely ionized atoms. Astronomers call such an object a “white dwarf.” A white dwarf is about the size of Earth, but with a mass density hundreds of thousands of times greater. These exotic objects are stable because a repulsive force of quantum-mechanical origins opposes the gravity that would otherwise cause it to collapse.



The 2002 Type Ia supernova in NGC 1309. (Photo credit: W. Li and A. V. Filippenko, University of California, Berkeley)

The luminosity of a Type Ia supernova is standard because nature prepares the explosion with laboratory precision, gradually adding material until the critical mass is achieved. The detonation occurs when the mass of the “bomb” exceeds the limit found by Subrahmanyan Chandrasekhar—1.44 solar masses, *exactly*.

How does this work?

If the separation of the binary stellar system is small enough, gravity can cause mass to flow from the normal star to the white dwarf. Inexorably, the mass of the white dwarf grows until it reaches 1.44 solar masses, when the entire star ignites as a giant thermonuclear bomb. *Voilà!*—the standard explosion of a Type Ia supernova.

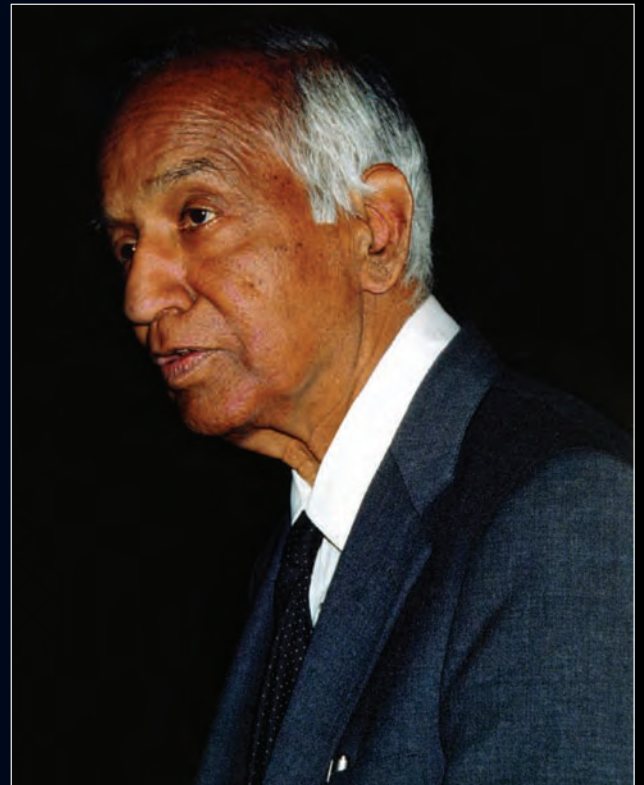
In the decades that have passed since the expansion of the universe was first recognized in 1929, larger and larger telescopes with increasingly sensitive instruments have enabled astronomers to observe Type Ia supernovas at greater distances. They reach back ever closer to the birth of the universe. Today, *Hubble* is the most powerful telescope for these observations, capable of observing a Type Ia supernova located three-quarters of the way back to the Big Bang.

was, in fact, expanding—as his basic theory predicted—he abandoned this repulsive antigravity term as unnecessary. Today, the idea of an additional repulsive force described mathematically by the cosmological constant, is firmly back at the forefront of astrophysics, and is named “dark energy”—because no one knows for sure what it physically is.

But what if there is an error in the straightforward explanation of the faintness of distant Type Ia supernovas? What if we are being fooled about their true distances, and tricked into thinking that we need dark energy to explain the observations? Are there alternative explanations?

In the late 1990s, some astronomers suggested that young galaxies could eject clouds of gray dust in large grains. Such dust could extinguish some of the light from Type Ia supernovas during its passage through intergalactic space. This extinction would cause Type Ia supernovas to appear fainter, and therefore farther away, than they actually are. (*Small* dust particles would affect red and blue light differently; the resulting color change would betray their presence—but such color changes are not observed.)

Another possibility was that these stellar explosions could have been less luminous in the past, perhaps due to changes in the composition of the gas from which their original stars formed. Heavy elements, such as carbon, oxygen, and iron, can only be created by nuclear reactions at the great pressures and temperatures found inside stars. At the end of their lives, these stars disperse the heavy elements into interstellar space, where the atoms can be swept up in a new generation of stars. Therefore, the interstellar material of the earliest galaxies, comprising the first generations of stars, lacked heavy



Beginning in 1931, Subrahmanyan Chandrasekhar (1910–1995), an eminent astrophysicist of Indian heritage, described the physics of white dwarfs in a series of scientific papers. In those papers, he showed that the repulsive force sustaining a white dwarf will be overcome by gravity—and the object will then collapse catastrophically—if the mass exceeds 1.44 solar masses. This is now called “the Chandrasekhar limit.” In 1983, he shared the Nobel Prize in Physics for this work; NASA’s *Chandra X-Ray Observatory* is named in his honor. (Photo credit: University of Chicago Press)



Supernova 1994D (the bright star at bottom left) in galaxy NGC 4526. The uniform brightness of certain types of supernovas allows astronomers to use them as distance indicators to scale the universe.

elements. Consequently, earlier and more distant Type Ia supernovas should also be deficient in heavy elements, which could possibly reduce their intrinsic brightness and lead astronomers to overestimate their distances.

Fortunately, we can test these alternative hypotheses, because they both predict the relative dimming of Type Ia supernovas should continue to be seen for those whose redshifts are greater than 1. These nominally correspond to objects about 8 billion light-years distant. This is in con-

trast to what one would expect if the universe actually began to accelerate in the more recent past, but was hindered from doing so earlier by a more influential force of gravity, acting on a then-smaller universe. If so, one should observe a relative brightening of Type Ia supernovas.

Only *Hubble* can reliably discover and measure the distances to Type Ia supernovas at such large distances. Our observing strategy was to obtain repeated, long exposures of 30 fields of the sky using the telescope's Advanced Camera for Surveys (ACS). We took the images through red and blue filters to make it easier to discover supernovas and make quick estimates of their redshifts. We examined each image closely, looking for flashes in small, faint galaxies. For promising candidates, we arranged follow-up observations to measure their changing brightness and spectra. On average, we found one Type Ia supernova at these great distances in every 10 ACS fields searched.

Over the course of 3 years, we have measured 135 supernovas of all types; 50 of these are Type Ia supernovas and about 25 of these have redshifts greater than 1. They approximately double the time span of the previously measured history of cosmic expansion.

Analysis of the new data show they are consistent with a universe in which a period of slowing expansion occurred before the more recent reversal (in the last 5 billion years or so) to accelerating expansion. The results are also inconsistent with the two leading alternative hypotheses of supernovas dimming due to dust extinction or chemical differences in earlier generations of stars.

Passing these tests and others, the ideas of acceleration and dark energy are gradually becoming established scientific knowledge. As astonishment gives way to acceptance, a new phase of investigation must now address the *nature* of dark energy—exploring the physical principles behind its existence and behavior. Until there is a complete and satisfying theoretical explanation, a comprehensive set of viable explanations—plus the experimental means to distinguish between them—must keep science moving in the right direction.

In summary, then, the latest supernova data from *Hubble* are consistent with the theory that the universe contains a mix of gravitationally attracting matter (both seen and unseen) and a repelling force dubbed “dark energy.” Dark energy is not a *new* constituent of space, but has been operating for most of cosmic history. Dark energy was already boosting the expansion rate as early as 9 billion years ago, but now clearly drives an accelerating rate.

Edwin Hubble wrote of the initial quest to measure cosmic expansion: “The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation.” We, the inquisitive passengers on the ship of science, must move from staring in disbelief at the spectacles before us, and work toward seeking to understand them.



Adam Riess is a professor of astronomy and physics at the Johns Hopkins University and a senior member of the science staff at the Space Telescope Science Institute, both in Baltimore, Maryland. Adam was born in Washington, D.C. He received his undergraduate education at the Massachusetts Institute of Technology, and his graduate schooling at Harvard University. He is an expert on observational cosmology using supernovas and Cepheid variable stars.