REVIEWS OF MODERN PHYSICS, VOLUME 84, JULY–SEPTEMBER 2012

Nobel Lecture: Accelerating expansion of the Universe through observations of distant supernovae*

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(published 13 August 2012)

DOI: 10.1103/RevModPhys.84.1151

This is not just a narrative of my own scientific journey, but also my view of the journey made by cosmology over the course of the 20th century that has lead to the discovery of the accelerating Universe. It is complete from the perspective of the activities and history that affected me, but I have not tried to make it an unbiased account of activities that occurred around the world.

20th Century Cosmological Models: In 1907 Einstein had what he called the "wonderful thought" that inertial acceleration and gravitational acceleration were equivalent. It took Einstein more than 8 years to bring this thought to its fruition, his theory of general Relativity (Norton and Norton, 1984) in November, 1915. Within a year, de Sitter had already investigated the cosmological implications of this new theory (de Sitter, 1917) which predicted spectral redshift of objects in the Universe dependent on distance. In 1917, Einstein published his Universe model (Einstein, 1917)—one that added an extra term—the cosmological constant—with which he attempted to balance gravitational attraction with the negative pressure associated with an energy density inherent to the vacuum. This addition, completely consistent with his theory, allowed him to create a static model consistent with the Universe as it was understood at that time. Finally, in 1922, Friedmann published his family of models for an isotropic and homogenous universe (Friedmann, 1922).

Observational cosmology really got started in 1917 when Vesto Slipher (to whose family I am indebted for helping fund my undergraduate education through a scholarship set up at the University of Arizona in his honor) observed about 25 nearby galaxies, spreading their light out using a prism, and recording the results onto film (Slipher, 1917). The results confounded him and the other astronomers of the day. Almost every object he observed had its light stretched to redder colors, indicating that essentially everything in the Universe was moving away from us. Slipher's findings created a conundrum for astronomers of the day: Why would our position as observer seemingly be repulsive to the rest of the Universe?

The contact between theory and observations at this time appears to have been mysteriously poor, even for the days before the internet. In 1927, Georges Lemâitre, a Belgian monk who, as part of his MIT Ph.D. thesis, independently derived the Freidmann cosmological solutions to general relativity, predicted the expansion of the Universe as described now by Hubble's law. He also noted that the age of the Universe was approximately the inverse of the Hubble constant, and suggested that Hubble's data and Slipher's data supported this conclusion (Lemâitre, 1927). His work, published in a Belgium journal, was not initially widely read, but it did not escape the attention of Einstein who saw the work at a conference in 1927, and commented to Lemâitre, *"Your calculations are correct, but your grasp of physics is abominable."* (Gaither and Cavazos-Gaither, 2008).

In 1928, Robertson, at Caltech (just down the road from Edwin Hubble's office at the Carnegie Observatories), predicted the Hubble law, and claimed to see it when he compared Slipher's redshift versus Hubble's galaxy brightness measurements, but this observation was not substantiated (Robertson, 1928). Finally, in 1929, Hubble presented a paper in support of an expanding universe, with a clear plot of galaxy distance versus redshift—it is for this paper that Hubble is given credit for discovering the expanding Universe (Hubble, 1929). Assuming that the brightest stars he could see in a galaxy were all the same intrinsic brightness, Hubble found that the faster an object was moving away from Slipher's measurements, the fainter its brightest stars were. That is, the more distant the galaxy, the faster its speed of recession. It is from this relationship that Hubble inferred that the Universe was expanding.

With the expansion of the Universe as an anchor, theory converged on a standard model of the Universe, which was still in place in 1998, at the time of our discovery of the accelerating Universe. This standard model was based on the theory of general relativity, and two assumptions: one, that the Universe is homogenous and isotropic on large scales; and two, it is composed of normal matter—matter whose density falls directly in proportion to the volume of space which it occupies. Within this framework, it was possible to devise observational tests of the overall theory, as well as provide values for the fundamental constants within this model—the current expansion rate (Hubble's constant), and the average density of matter in the Universe. For this model, it was also possible to directly relate the density of the Universe to the rate of cosmic deceleration: the more material, the faster the deceleration; and the geometry of space: above a critical density, the Universe has a finite (closed) geometry, below this critical density, a hyperbolic (open) geometry.

In more mathematical terms: If the universe is isotropic and homogenous on large scales, the geometric relationship of space and time are described by the Robertson-Walker metric,

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2\right]. \tag{1}$$

In this expression, which is independent of the theory of

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[*] The 2011 Nobel Prize for Physics was shared by Saul Perlmutter, Adam G. Riess, and Brian P. Schmidt. These papers are the text of the address given in conjunction with the award.

gravitation, the line element distance (s) between two objects depends on coordinates r and θ, and time separation, t. The Universe is assumed to have a simple topology such that if it has negative, zero, or positive curvature, k takes the value $\{-1, 0, 1\}$, respectively. These universes are said, in order, to be open, flat, or closed. The Robertson-Walker metric also requires the dynamic evolution of the Universe to be given through the evolution of the scale factor $a(t)$, which gives the radius of curvature of the Universe—or more simply put, tracks the relative size of a piece of space over time. This dynamic equation of the Universe is derived from general relativity, and was first given by Friedmann in the equation which we now name after him:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}. \tag{2}$$

The expansion rate of the Universe (H), called the Hubble parameter (or the Hubble constant, H_0, at the present epoch), evolves according to the content of the Universe. Through the 20th century, the content of the Universe was assumed to be dominated by a single component of matter with density, ρ_i, compared to a critical density, ρ_{crit}. The ratio of the average density of matter compared to the critical density is called the density parameter, Ω_M and is defined as

$$\Omega_i = \frac{\rho_i}{\rho_{\text{crit}}} \equiv \frac{\rho_i}{(3H_0^2/8\pi G)}. \tag{3}$$

The critical density is the value where the gravitational effect of material in the Universe causes space to become geometrically flat [$k = 0$ in Eq. (1)]. Below this density, the Universe has an open, hyperbolic geometry ($k = -1$); above, a closed, spherical geometry ($k = +1$).

As experimentalists, what we need are observables with which to test and constrain the theory. Several such tests were developed and described in detail in 1961 by Allan Sandage (Sandage, 1961) and are often described as the classical tests of cosmology. These tests include measuring the brightness of an object as a function of its redshift. The redshift of an object, z, indicates the amount an object's light has been stretched by the expansion of the Universe and is related to the scale factor such that

$$1 + z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = \frac{a(z=0)}{a(z)}. \tag{4}$$

The redshift is measured from the observed wavelength of light, λ_{obs}, and the wavelength at which it was emitted, λ_{emit}.

The luminosity distance, D_L, is defined from the inverse square law of an object of luminosity, L, and observed flux, f,

$$D_L \equiv \sqrt{\frac{L}{4\pi f}}. \tag{5}$$

This was traditionally solved as a Taylor expansion to Eqs. (1) and (2),

$$D_L \approx \frac{c}{H_0}\left[z + z^2\frac{(1-q_0)}{2}\right], \tag{6}$$

where c is the speed of light, H_0 the current cosmic expansion rate has units of velocity over distance, and the deceleration parameter, q_0, is defined as

$$q_0 \equiv -\frac{\ddot{a}_0}{\dot{a}_0^2} \qquad a_0 = \frac{\Omega_M}{2}. \tag{7}$$

The equivalence of Ω_M and q_0 is provided through solutions of the Friedmann equation assuming a universe consisting solely of normal matter. The Taylor expansion is accurate to a few percent over the region of interest of the day ($z < 0.5$), but was perfected by Mattig (1958), who found a closed solution,

$$D_L = \frac{c}{H_0 q_0^2}[q_0 z + (q_0 - 1)(\sqrt{1 + 2q_0 z} - 1)]. \tag{8}$$

These equations provide one of the classic tests of cosmology—the luminosity distance versus redshift relationship. For an object of known luminosity, a single measurement at a moderate redshift [not so low that gravitationally induced motions, typically $z \sim 0.002$, are important—and not so high that the second order term in Eq. (6) is important], of its redshift and brightness, will yield an estimate of H_0. By measuring a standard candle's (an object of fixed luminosity) brightness as a function of redshift, one can fit the curvature in the line, and solve for q_0.

In principal, from Eq. (6), measuring H_0 does not appear to be difficult. An accurately measured distance and redshift to a single object at a redshift between $0.02 < z < 0.1$ is all that it takes, with their ratio providing the answer. But making accurate absolute measurements of distance in astronomy is challenging—the only geometric distances that were typically available were parallax measurements (measurement of the wobbles in the positions of nearby stars due to the Earth's motion around the Sun) of a handful of nearby stars. From these few objects, through a bootstrapping process of comparing the brightnesses of similar objects in progressive steps, known as the extragalactic distance ladder, researchers came to conclusions which varied by more than a factor of 2, a discordance which persisted until the beginning of the new millennium.

Measuring q_0 required making accurate measurements of the relative distances [absolute not required since the Hubble constant can be normalized out of Eqs. (6) and (8)]. Attempts made in the 1950s (Humason, Mayall, and Sandage, 1956), based on the brightest objects in the sky, giant galaxies in the center of clusters, provided a range of answers. Ultimately, Tinsley (1972) showed that these galaxies should change dramatically in brightness as we look back in time, making them problematic cosmological probes. Progress in measuring q_0 required a precise standard candle bright enough to be seen to $z > 0.3$, where curvature in the luminosity distance redshift relationship could be accurately measured.

Supernovae and my Career: The beginning of my astronomical career started in 1985 when I arrived as a bright-eyed freshman at the University of Arizona studying physics and astronomy. In my first astronomy class I felt daunted by all of the astronomy majors, many of whom seemed to me to have encyclopedic knowledge of everything from white dwarf stars to quasars. I understood physics, but I knew nothing of all of these things, so I looked around for something to do at Steward Observatory to increase my knowledge, and started working for John McGraw on his CCD transit instrument (CTI, Fig. 1).

This instrument was 15 years ahead of its time, and made the first large digital maps of the sky. Employing charged coupled devices (CCD), Cerro Tololo Inter-American Observatory (CTIO) did not track the sky, instead it let the night sky pass overhead, and followed the motion caused by the Earth's rotation electronically, using a technique known as drift scanning. The Sloan Digital Sky Survey applied this technique with its highly successful survey starting in 2000. In 1985, CCDs were still very young, and the data rates that this telescope achieved in the mid 1980s were staggering. This data rate pushed the software and computational hardware capabilities of the day to the detriment of the telescope's overall scientific impact. As with all undergraduates, my progress was slow, but by the end of my 3rd year I had a real job within the group, to try to come up with ways to discover exploding stars known as supernovae in this data set. With a newly minted classification, type Ia supernovae were reputed to be good standard candles, and the CTI instrument had the opportunity to obtain the first digital light curves of a set of objects at redshifts greater than $z > 0.01$ where they could be tested as standard candles. The task was hard because the data set was enormous and, for computational reasons, we only had the ability to search catalogs of objects. Supernovae, though, usually occur in galaxies, and when making catalogs it is difficult to discern new objects in the complex structure of a galaxy. By the time I finished my undergraduate degree, I had managed to discover a possible object. Unfortunately, it was in data that was more than a year old, and was therefore never confirmed.

Supernovae: Supernovae (SN), the highly luminous and physically transformational explosions of stars show great variety, which has lead to a complex taxonomy. They have historically been divided into two types based on their spectra. Type I supernovae show no hydrogen spectroscopic lines, whereas type II supernovae have hydrogen. Over time, these two classes have been further divided into subclasses. The type I class is made up of the silicon rich type Ia, the helium rich type Ib, and the objects which have neither silicon nor helium in abundance, type Ic. The type II class is divided into II-P, which have $a \approx 100$ day "plateau" in their light curves, II-L which have a "linear" decline in their light curves, and II-n which have narrow lines in their spectrum (Filippenko, 1997).

Massive Star Supernovae: Massive stars typically undergo core collapse as the last amount of silicon is burned to iron in their cores. As pressure support is removed by the loss of heat previously supplied by nuclear reactions, their interiors collapse to neutron stars, and a shock wave is set up by neutrino deposited energy outside of the neutron star region. A massive star that has a substantial, intact hydrogen envelope produces a SN II-P. Other variants are caused by different stages of mass loss. SN Ib represent a massive star which has lost its hydrogen envelope, and SN Ic are objects which have, in addition, lost their helium envelope.

Thermonuclear Detonations: These explosions are the result of the rapid burning of a white dwarf star. The entire star is burned, mainly to ^{56}Ni, but also to intermediate mass elements such as sulfur and silicon. The actual mechanism has long been assumed to occur when a white dwarf star accretes mass from a companion, and approaches $1.38M_{\odot}$. In 1931, Chandrasekhar showed at this point a white dwarf's self-gravity will exceed the pressure support supplied by its electron degenerate gas (Chandrasekhar, 1931). As the star approaches this critical juncture, the high pressure and density in the star's core initiates carbon burning near its center, which eventually leads to the entire star being consumed by a rapidly expanding thermonuclear burning front. We now suspect that it may be possible to ignite such an explosion in a variety of ways. These include sub-Chandrasekhar explosions initiated by a surface helium detonation which compresses the star's center to its nuclear flash point, and super-Chandrasekhar explosions involving the merger of two white dwarfs via gravitational radiation.

FIG. 1 (color). CTI Telescope at Kitt Peak Arizona.

Graduate School at Harvard: Late in 1988, I applied to a number of universities with the hope of receiving a scholarship to work on my Ph.D.—I was not particularly optimistic as I had heard horror stories from others about how competitive the process was. To my surprise, on my 22nd Birthday (24 Feb 1989), I received a call from Bob Kirshner at Harvard University, telling me of my acceptance to Harvard's Ph.D. Astronomy program. It was the best birthday gift of my life. This call was followed up with several more offers in the coming hours and days, and I had a hard choice of deciding where to study. Either I could stay in the west of the United States where I was comfortable, or move to the east, which was tantamount to a foreign country to me. After visits to several campuses, Harvard had risen to the top of my list, a decision which I finalized when Bob Kirshner visited Tucson to give the first Aaronson Memorial Lecture by asking if I could work with him on my Ph.D.

When I arrived at Harvard to work with Bob Kirshner, I decided to focus on studying supernovae rather than discovering them. The idea of measuring the Hubble constant appealed to me, and so we took the tact of building on my supervisor's thesis, to calibrate the luminosity of type II supernovae and use them to measure the extragalactic distance scale (Kirshner and Kwan, 1975). SN 1987A, the nearest observed supernova to the Earth in almost 400 years had created a frenzy of activity in the subject, and Bob's finishing Ph.D. student, Ron Eastman, had developed a sophisticated computer code to model how radiation emerged from this supernova. My thesis involved applying Ron's theory to several supernovae at sufficient distances so that we could reliably estimate the Hubble constant. Type II-P supernovae are well suited to this purpose because they have simple hydrogen based atmospheres, whose emergent flux is close to a blackbody. In addition, their expansion is unaffected by gravity, enabling us to infer their radius by making measurements over time using absorption lines in their spectra to indicate the velocity of the material from which the supernova's flux is emerging. Put together, the emergent flux calculations and expansion rate allow the distance to a supernova to be determined on a purely physical basis. We named the method the expanding photosphere method (EPM).

In addition to observations, this method has as an essential ingredient, atmospheric models to calculate the correction to the blackbody assumption. Ideally, these calculations would be handcrafted for each SN, but the calculations took weeks to run, and instead, we used an approximation where we found that the blackbody correction depended almost entirely on the SN's temperature, and not on other factors. For my thesis, I used this technique to measure the distances to 14 SN II at redshifts between $0.005 > z > 0.05$, and found a 95% range for the value of the Hubble constant to be $61 < H_0 < 85$ km/s/Mpc (Schmidt *et al.*, 1994). This result was completely independent of the cosmic distance ladder—the bootstrapping of distances from our solar system to the nearest galaxies, but was in almost perfect accord to galaxies who distances were determined using Cepheid variable stars as part of the Hubble Key Project. The accepted value today is $67 < H_0 < 75$ km/s/Mpc. Work on using type II SN to measure distances continues, and while some of the approximations made during my thesis have been challenged, the fundamental technique remains in place.

After my thesis, the next step was obviously to use these objects to measure the deceleration parameter, q_0, but SN II and the expanding photosphere method have three significant drawbacks in measuring the global properties of the Universe. The first is that SN II are difficult to observe beyond a $z > 0.3$ with current instrumentation—they are too faint. The second is that they require significant observations to obtain each distance—multiepoch high quality spectra with simultaneous photometric observations, making them observationally prohibitively expensive for measuring q_0. The final difficulty is that the EPM distance precision, while not poor at about 15%, means many objects need to be observed to make a sufficiently precise measurement of q_0 to be interesting. The principal advantage of EPM, that objects were calibrated in an absolute sense, while essential for H_0 measurements, was irrelevant in q_0 measurements. Fortunately, during my Ph.D., I was exposed to the rapidly emerging work directed at measuring distances to type Ia supernovae. More importantly, I had got to know and work with the world experts on these objects, and these relationships were ultimately the basis of forming the High-Z SN Search Team.

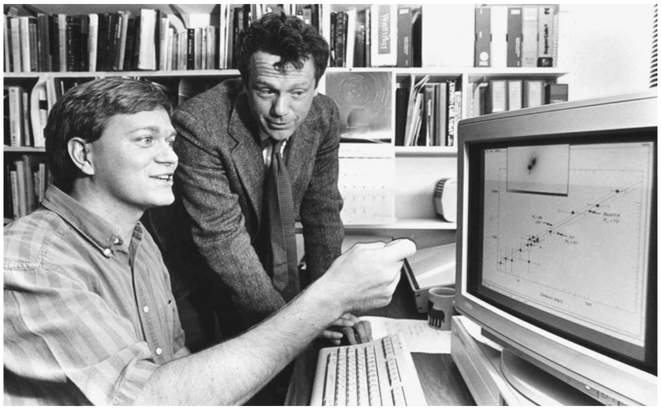


FIG. 2. Bob Kirshner examing my thesis results at Harvard in 1993.

The Foundations of the High-Z Team: When I arrived at Harvard in 1989, I arrived with Bob's newest postdoc, Swiss national, Bruno Leibundgut. Bruno, rather than studying SN 1987A and its sibling type II supernovae like most of the world was doing at the time, had concentrated on understanding just how standard of candles type Ia supernovae were. Type Ia supernovae, and their antecedents type I supernovae, had developed a reputation from less than ideal data for being essentially identical, making them potentially very good cosmological probes.

For his thesis, Bruno spent many a night on telescopes in Chile, taking photographic images to discover objects in a project lead by his supervisor Gustav Tammann, and collaborator Allan Sandage. While this project successfully discovered supernovae, the search was unable to deliver a data set useful for testing the veracity of SN Ia as standard candles. So Bruno used the entirety of data collected over the previous 5 years, and by other groups previously, to develop a standard template of the average SN Ia light curve which could be used as a reference to test the homogeneity of the SN Ia family. The results were extremely encouraging—all of the SN Ia seemed to fit a single template (Leibundgut, 1988). Now at Harvard, Bruno was able to use Harvard facilities, the new 1.2 m telescope equipped with a CCD to monitor the light curves of nearby SN Ia as they were discovered, and the huge Multiple Mirror Telescope to obtain their spectra. Our first observing trip together, soon after we both arrived to Harvard, resulted in what I believe are the only ill feelings ever between Bruno and myself. We had trouble understanding each other's enthusiasm for thinking we knew the right way to observe. The fact that Bruno was the postdoc and I the student did not occur to me at the time as being a key factor in the discussion. Within a few months, though, we grew to know and respect each other—and to this day, if Bruno challenges anything I say or do, I listen first, and ask questions later.

Bruno's first scientific big break at Harvard came with SN 1990N, an object that was discovered in the summer of 1990, just as Bob and I were off to Europe for a summer school on Supernovae at Les Houches in the French Alps. This object was discovered extremely soon after explosion, and its spectrum showed some funny features that persisted and were different to other SN Ia. But SN 1990N's light curve was well matched by Bruno's template (Leibundgut *et al.*, 1991).

In Les Houches I realized just how lucky I was to be an astronomer. A gorgeous village at the base of Mount Blanc, the summer school immersed me for 5 weeks in a group of students from around the world, tutored by the greats of the field. I consider it to be the greatest 5 weeks of my life. There I met a young Chilean, Mario Hamuy, who was working at Cerro Tololo Inter-American Observatory as a research assistant for CTIO staff astronomer Nick Suntzeff. I was familiar with Mario by reputation, for the photometric data he and Nick had amassed on SN 1987A in the Large Magellanic Cloud, which I was using to measure this supernova's distance as part of my thesis.

Mario told us of a new project, the Calan/Tololo survey, which would use the Curtis Schmidt telescope at CTIO to discover objects at redshifts more distant than the objects we were all studying. By discovering SN at $0.02 < z < 0.1$, the Calan/Tololo survey aimed to test rigorously SN Ia as standard candles, using the redshift as an accurate proxy for relative distance. The members of this group, Mario Hamuy, Nick Suntzeff, and Mark Phillips, at CTIO, and Jose Maza at the University of Chile, were starting their program that year. In addition to Nick and Mario's work on SN 1987A, Jose Maza had lead a highly successful SN search from Calan in the 1980s, while Mark had made an impact in the field by observing SN 1986G in the nearby Centaurus A galaxy. SN 1986G was one of the first objects to be observed with a CCD, and showed a light curve that was ultimately accepted as being unusual compared to the Leibundgut template.

Partially as a result of the Les Houches school, and mainly due to subsequent work that Bob Kirshner was doing with Mark Phillips and Nick Suntzeff on SN 1987A, a 5 week trip for me to visit Cerro Tololo was planned for the end of 1991. There I would use data from the Calan/Tololo survey on type II SN for my thesis—and learn the techniques that were being used at CTIO to accurately measure the light curves of SN Ia using CCDs, and apply them to my SN II. To ensure that the cultural shock was not too great, my trip was sequenced with the arrival to CTIO of another of Bob Kirshner's graduate students, Chris Smith, who was about to start his first postdoc at the observatory.

I arrived in Santiago from the long flight from Miami, and was taken to the bus station for a 6 hour bus trip to La Serena. There I met Pete Challis from the Space Telescope Science Institute who was also on his way to CTIO, but in his case for a long observing run. In the 6 hours to La Serena, Pete and I covered a lot of ground, and we soon established that Pete had been at Michigan as an undergraduate with my Ph.D. supervisor, Bob Kirshner, and was interested in changing jobs. I told Pete that Bob was looking for someone to help him manage his Hubble Space Telescope observations, and in that way Pete and Bob were reconnected, and they continue to work together to this day.

When we arrived at La Serena, I was met by Mario Hamuy and Mark Phillips, who were, in addition to picking me up, putting a wooden box full of photographic plates from the Curtis Schmidt Telescope onto the bus for its return journey to Santiago. While I slept, the photographic plates made their journey south to the University of Chile where Jose Maza and his team would search them the following day for supernovae.

The Calan/Tololo survey used this technique to efficiently discover more than 50 objects from 1990–1993. The Calan/Tololo survey had regularly scheduled CTIO-4 m and CTIO-1.5 m time to obtain spectra as they were sufficiently regular at discovering objects that they could plan in advance on their discoveries. For photometry, because they only needed a small amount of time, they borrowed time from cooperative astronomers observing on CTIO telescopes who enjoyed the excitement of observing an astronomical object that changed over the course of a few nights.

A few days after arrival, I asked Mario how his work on SN Ia was going, and he said he was depressed. He showed me his first couple of objects, and one of them, SN 1990af, looked pretty normal with respect to its spectrum, but compared to Bruno's template, it clearly rose and fell more quickly, More significantly, SN 1990af was significantly fainter than the other objects in their sample, despite being at the same redshift. He felt that the Calan/Tololo program to use SN Ia to measure H_0, and eventually q_0, had run into a snag—the objects they were planning to use to measure distances were not living up to their reputation—they were not standard candles.

1991 was a transformational year for SN Ia. Early in the year, a nearby galaxy hosted SN 1991 T. In a paper lead by Mark Phillips that included both the Tololo and Harvard groups (Phillips *et al.*, 1992), as well as a paper lead by Alex Filippenko (Filippenko *et al.*, 1992), the object was shown to be highly unusual. Its spectrum had extra features early on but was largely missing the most recognized feature of the class, a strong silicon line at 6130 Å. In addition, the light curve rose and fell significantly more slowly than average and it seemed to be too bright given its host galaxy's distance. Between uncertainties in the amount of dust obscuring the object and the distance to its host galaxy, we could not be absolutely certain that this object was brighter than other SN Ia, although work done by Jason Spyromilio at the Anglo-Australian Observatory indicated that SN 1991 T produced more iron than is typical for normal SN Ia (Spyromilio *et al.*, 1992).

Later in the year, another object, SN 1991bg, occurred in a nearby elliptical galaxy. In papers lead by Leibundgut (Leibundgut *et al.*, 1993) (Harvard and Tololo groups) and Filippenko (Filippenko, 1992), this object was shown to have a different spectrum from the norm, and a light curve that faded much more quickly than average. In this case, the object was so much fainter than average, with no evidence of any obscuring dust, that the case was clear.

By 1993, based on the range of objects being studied in the nearby universe, and consistent with the picture that was emerging from the Calan/Tololo survey, Mark Phillips wrote his seminal paper which compared the rate that an object faded to its luminosity, finding that faster evolving objects were systematically fainter than their slower evolving siblings (Phillips, 1993). I remained a bit skeptical—while SN 1991bg was clearly different, the objects in Mark's 1993 paper were all in the nearby Universe, and the objects' distances uncertain. I felt that it was possible that the whole correlation might go away, if only SN 1991bg were thrown out. But this paper got the world thinking, and amongst those were Bob Kirshner, whose new Ph.D. student Adam Riess was looking for a project for his thesis. Bob focused Adam's attention at using the statistical expertise of Bill Press (who was one floor down at the Center for Astrophysics) to develop a technique to model SN Ia light curves and estimate their distances.

I was finishing my thesis on SN II-P during this time, but spent a lot of time talking to Adam about his project. The emerging picture of SN Ia was just so interesting, despite the need for me to write up, I could not stop from thinking about how to use SN Ia to measure distances. I submitted my thesis in August 1993, and stayed on at the Center for Astrophysics as a Harvard-Smithsonian Center for an Astrophysics Postdoctoral Fellow, where I had the benefit of a fellowship to do anything I wanted, but with the opportunity of being embedded in the expertise of Bob Kirshner's group.

Early in 1994, Mario Hamuy from the Calan/Tololo group visited. The Calan/Tololo group had expanded to include Bob Schommer, a CTIO astronomer who had experience in measuring the Hubble constant using the Tully-Fisher technique, and Chris Smith (another Kirshner student), whose all-around observational and analysis experience was being used to help analyze the SN light curves. Mario was armed with Calan/Tololo's first 13 SN Ia light curves and redshifts and to me what was an astonishing discovery. If they applied Mark Phillips' relationship to this independent set of objects, the scatter about the Hubble law dropped dramatically and demonstrated that tSN Ia provided distances with a precision better than 7% per object. This was much better than anything I thought could ever be achieved. The Calan/Tololo group allowed Adam to train up his new statistical method with these data—they were at sufficient distance that their relative distances could be inferred with high accuracy from their redshifts—thereby removing one of the principal problems in previous SN Ia distance work.

A month later, during one of the groups observing runs at the Multiple Mirror Telescope (MMT), Bob Kirshner, Adam Riess, and Pete Challis received a call from Saul Perlmutter of the Supernova Cosmology Project (SCP) to follow up a high redshift supernova candidate of theirs. The SCP had struggled to find distant SN Ia over the previous 5 years, but I was excited by the spectrum I saw the following morning from the MMT. Pete had already reduced the data and had eye balled it as a type Ia SN at a redshift of $z = 0.42$, something I confirmed during the day from the comfort of my CfA office. In the ensuing weeks, as we negotiated with Saul's team to publish the spectrum in the International Astronomical Union Circulars, we realized that this event was not alone—the SCP had discovered several such objects in the previous months.

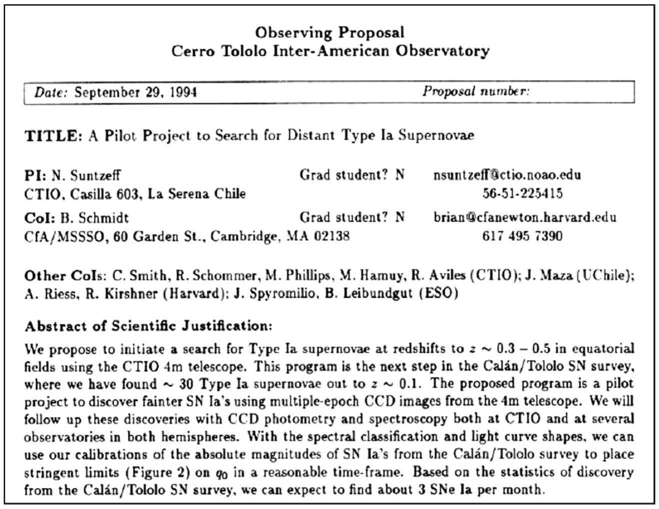
These two events—the development of the ability to measure precise distances with SN Ia, and the capacity to discover these objects in the distant Universe, were the ingredients necessary to finally mount a successful campaign to measure the deceleration parameter. The Supernova Cosmology Project had been working towards this goal since 1988, but it became clear that they had significantly different views on how to approach the problem—especially with respect to measuring precise distances—than my supernova colleagues and I had.

FIG. 3 (color). Brian Schmidt, Pete Challis, and Nick Suntzeff discussing the High-Z SN Search at Cerro Tololo.

The High-Z Team: Measuring the Deceleration Rate of the Universe: In mid-1994 I went to CTIO for an observing run for a project on clusters that ultimately did not pan out. While I stayed on at CTIO after observing, Nick Suntzeff and I hatched a plan to use the CTIO 4 m to mount our own campaign to measure q_0, given that the two essential ingredients were suddenly in place. Measuring q_0 had always been part of the plan of the Calan/Tololo survey, but opportunity knocked a few years earlier than the group had anticipated.

Type Ia supernovae are not common objects, they occur in a galaxy like the Milky Way a few times per millennium. Since SN Ia take approximately 20 days to rise from nothingness to maximum light, observing the same piece of sky twice with a one month separation (which equates to 20 rest-frame days at $z = 0.5$) will yield objects which are typically near maximum light, and therefore young enough to be useful for measuring precise distances. The CTIO 4 m telescope was equipped with a state-of-the-art 2048×2048 pixel CCD that covered the widest field of view of a 4 m telescope at the time. The weather at CTIO was also impeccable through the Chilean summer—so there would be virtually no chance of being weathered out in a supernova search. This was essential because the experiment required images taken a month apart to be compared, and additional preplanned telescope time afterwards to follow up the candidates. Bad weather at any of these times would prove fatal for the experiment, leaving no candidates and lots of telescope scheduled to observe objects that did not exist. This is a problem I knew that the SCP had faced many times.

Nick and I soon enlisted Mark Phillips, Mario Hamuy, Chris Smith, and Bob Schommer (CTIO), and Jose Maza (University of Chile) from the Calan/Tololo SN Search. We also brought on Bruno Leibundgut and Jason Spyromilio,



Observing Proposal
Cerro Tololo Inter-American Observatory

Date: September 29, 1994 *Proposal number:*

TITLE: A Pilot Project to Search for Distant Type Ia Supernovae

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Abstract of Scientific Justification:

We propose to initiate a search for Type Ia supernovae at redshifts to $z \sim 0.3 - 0.5$ in equatorial fields using the CTIO 4m telescope. This program is the next step in the Calán/Tololo SN survey, where we have found ~ 30 Type Ia supernovae out to $z \sim 0.1$. The proposed program is a pilot project to discover fainter SN Ia's using multiple-epoch CCD images from the 4m telescope. We will follow up these discoveries with CCD photometry and spectroscopy both at CTIO and at several observatories in both hemispheres. With the spectral classification and light curve shapes, we can use our calibrations of the absolute magnitudes of SN Ia's from the Calán/Tololo survey to place stringent limits (Figure 2) on q_0 in a reasonable time-frame. Based on the statistics of discovery from the Calán/Tololo SN survey, we can expect to find about 3 SNe Ia per month.

FIG. 4. The original High-Z SN search team proposal.

who were now at the European Southern Observatory, as well as Bob Kirshner, Pete Challis, Peter Garnavich, and Adam Riess from Harvard. This provided the observational fire power for both discovering SN Ia, and for following up our discoveries.

The proposal was due as my first child, Kieran, was being born, and Nick Suntzeff and Bob Schommer polished up our team's proposal, and submitted it on September 29, 1994 (Fig. 4).

I had successfully applied for a postdoctoral fellowship in Australia at the Mount Stromlo Observatory, and so in my last few months at the CfA at the end of 1994, I started writing a supernova discovery pipeline. Supernovae are not always easily identified as new stars on galaxies—most of the time they are buried in their hosts, and cannot just be identified without a more sophisticated technique. From colloquia, I knew that the SCP had developed some sort of image subtraction pipeline, and that was the technique they had used to successfully discover their distant objects.

As part of my thesis I had developed techniques of automatically aligning images, but the Earth's atmosphere blurs each image differently, making the shape of a star on each image, known as its point spread function, unique. I had met Drew Phillips at CTIO, and he had developed a technique for convolving images with a kernel to match two images' point spread functions, thereby enabling a clean image subtraction. I used this package as the basis of our pipeline, and set about developing a series of scripts to automatically subtract the massive amounts of data we would get in early 1995. These programs were meant to take the gigabytes of imaging data that we gathered in a night, align it with the previous epoch, and then match and scale the image point spread functions between the two epochs to make the two images as identical as possible. These two images are subtracted with the differenced image searched for new objects, which stand out against the static sources that have been largely removed in the differencing process.

During my last months at the CfA, Bob Kirshner's new postdoc, Peter Garnavich, arrived. Peter was busy principally working on SN 1987A and another nearby object, SN 1993J, during this time, but he was a new colleague with fresh ideas with whom I could discuss the High-Z program with. We instantly became friends, and despite our short overlap at the CfA, Peter is a colleague I have always known I could trust through good times and bad. By the time I left for Australia, using some test data, I felt I had a discovery program that more or less worked.

When I arrived in Australia, I had a few weeks to get myself settled before our first observing run started in Chile. I had decided that I would stay put in Australia, rather than travel to Chile, since we were still in the middle of moving, with my wife starting her job and our 4 month old son proving not to be the great sleeper we had hoped for. As we started to implement the pipeline at CTIO it became clear we had a problem or two. The CTIO computing system, which I thought was a lot like my own in Australia, had substantial differences which prevented the software from running. To confound matters, the internet connection between Australia and Chile was about 1 character per second—making it almost impossible for me to do anything remotely. Working with a very patient Mario Hamuy, we slowly marched through the problems. I would email Mario snippets of code to be inserted in the subtraction program, with Mario reporting back how it worked.

Our first observations were taken on February 25th, 1995, and we had another night's data on March 6th. The processing of these data was an unmitigated disaster—nothing seemed to work, and I could not get the data to Australia to diagnose what was going wrong. We used a courier company to express tapes of data to Australia so I could work to fix problems, but that delivery was lost and never arrived. Now, working with the entirety of the CTIO collaboration, we slowly pieced the pipeline together, making it email tiny 16×16 pixel stamps of interesting things to me in Australia. These little mini images, combined with as vivid descriptions as could be mustered by telephone, were all that I had to figure out what was going wrong, or right. We had two nights on March 24th and 29th, and a proposal to write for a continuation of our program, due on the 30th of March. Around the 27th of March, suddenly the stamps that were being sent to me started producing objects that looked interesting. Several were asteroids—we could tell they were moving—but one was on the outskirts of a galaxy. This object was detected on March 6th, but was not visible on the data of March 24th (the data from this night were poor, so we could not confirm that it was not an asteroid). With these candidates, we submitted the continuation of our program, and set about searching the data from March 29th. Stamp after endless stamp arrived in Australia, and suddenly one, C14 as it was named, looked interesting. It was a new object, buried in a spiral galaxy—it did not move, and it appeared possibly fainter in our poor data from March 24th (Fig. 5). I excitedly called CTIO and the report back from looking at the whole image was positive. Yes, it looked like a supernova.

Using the CTIO-4 m spectrograph, Mark Phillips was able to obtain a spectrum of the galaxy—it was at a redshift of $z = 0.48$—making it potentially the most distant SN yet detected. But this spectrum showed no hint of the supernova, its light was overwhelmed by its host galaxy's. Bruno and Jason had follow-up time with the European Southern

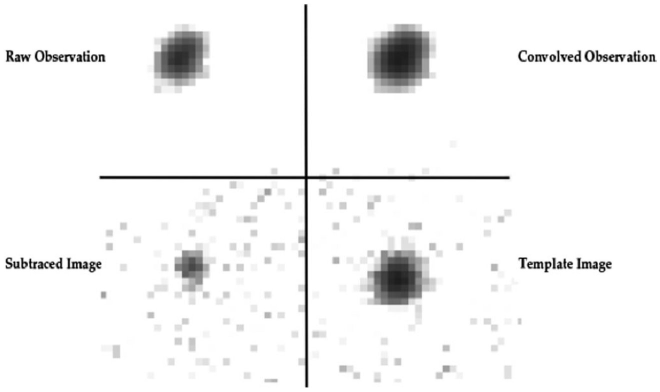

FIG. 5. Original stamps for candidate C14—complete with typos. This object was confirmed as SN 1995 K, which at $z = 0.479$, was the most distant SN Ia yet discovered in April, 1995. The observation taken on March 29th (upper left) was matched (upper right) to the observation taken in February (lower right), and subtracted (lower left).

Observatory (ESO) New Technology Telescope (NTT) at La Silla on April 3rd. Through heroic effort (they observed the object all night) and data reduction—it took a week, the NTT spectrum showed the object was indeed a SN Ia. In writing the IAU circular, we needed to come up with a name for our team—for lack of anything better, we settled upon the High-Z SN Search team.

In the days that followed, Nick, Mark, and Bob Schommer convinced Allan Dressler at Carnegie to take a series of images of SN 1995 K with the DuPont telescope at Las Campanas. That data, combined with that taken at ESO and CTIO, provided what is still a very good light curve of a distant SN Ia. We presented the light curve and its place on the Hubble diagram September 1995 in our application for telescope time. While 1995 K showed $q_0 = -0.6$, the uncertainty was such that we required at least 10 objects to make a statistically significant measurement, and we did not give the actual value much thought (Fig. 6).

Supernova aficionados Alejandro Clocchiatti (Catolica University) and Alex Filippenko (Berkeley), along with non-supernova experts John Tonry (Hawaii), Chris Stubbs, and Craig Hogan (University of Washington), were all recruited to the team in 1995 bringing along specific skills and additional telescope time resources.

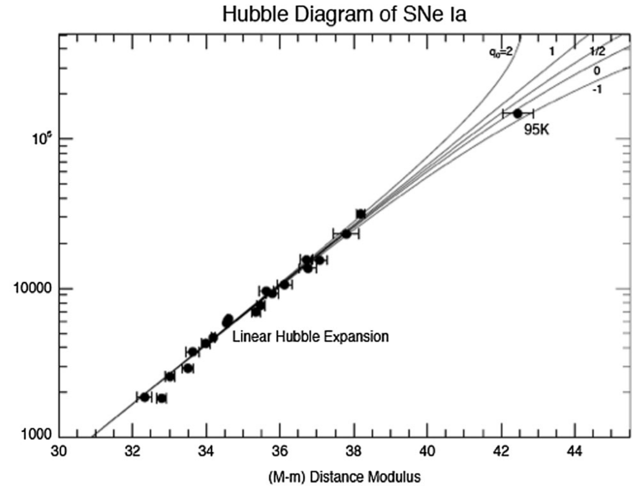

FIG. 6. SN 1995 K on the Hubble Diagram from our September 1995 telescope proposal.

Alejandro Clocchiatti undertook his Ph.D. thesis at the University of Texas studying type Ib/c SN—likely contaminants in our experiment which we needed control using his expertise. Alejandro was also resident in Chile where we could use his physical presence in helping executing observations, as well as providing us additional access to Chilean telescopes.

Alex Filippenko, a member of the community that studied supernovae, had approached me in 1995 to join the High-Z Team. We turned him down on the basis that we did not want to be seen as poaching a member from a competing team. By the end of 1995 it became clear that Alex's expertise and access to Keck were going to be essential for us to successfully undertake our experiment to measure on q_0. So when he asked again in 1996 to join our team, we immediately said yes.

John Tonry, in addition to providing access to telescope time through the University of Hawaii, is widely regarded as one of the most capable observational astronomers of our era. On my trips to Hawaii, John and I would discuss the current deficiencies in our experiment, and John would inevitably write new programs to assist with our discovery and analysis of SN Ia. In these bursts of programming, John developed our interactive search tool, our spectral analysis tool (SNID, which is still widely used by the community), and the core of our photometric analysis pipeline.

Chris Stubbs was one of the members of the MaCHO gravitational microlensing experiment which operated the Mount Stromlo 50 inch telescope, and he brought significant experience in analyzing large data sets, which our group sorely lacked.

Craig Hogan was an eminent theorist who had taught me cosmology at the University of Arizona before he moved to the University of Washington. I felt (and still feel) that it was important to have at least one theorist on any large observational program, and Craig was someone whose theoretical grounding was well matched to the needs of our team.

Given the dispersed nature of our team, we had to gather each year to discuss how the observational program was progressing, and how we were going to turn all of the our data into a definitive measurement of q_0. Our first meeting was in 1996 at Harvard. We had just been awarded Director's Discretionary time with the Hubble Space telescope, and we needed to plan on how to use this great resource effectively. We decided to expand our discovery platform to include the new wide field camera on the Canada France Hawaii Telescope, in Mauna Kea, with University of Hawaii astronomer and High-Z team member, John Tonry, providing access to this unique facility. Running SN searches on two telescopes, twice per year, made me and the team very busy people.

Each observing run was organized chaos. I would arrive a week early, with the latest version of the software. Since we did not have dedicated equipment, the whole pipeline would be rebuilt at the beginning of each run—and this never proceeded smoothly. Each facility had its own sets of operating systems that, while all UNIX, were sufficiently different that the code had to be individually compiled for each system. Because of the size of our data set, we needed to operate across multiple machines and disks—hardware that changed each run. This week inevitably ended with the entire team working 20 h days to ensure that we were able to promptly discover supernovae. This level of effort led to interesting coping strategies—Bob Schommer was famous for playing James Brown at high volume in the telescope control room. It also lead to the occasional mistake. One night in the CTIO-4 m control room as Alejandro Clocchiatti watched as I frenetically typed, Alejandro suddenly turned pale and said, "I do not think you wanted to do that." I had just accidentally deleted the night's data. While we pondered how to tell Nick (who was manning the telescope) the news, Nick suddenly screamed, "What happened to all the data?" I saw my career flash before my eyes, but we soon realized the data were stored (in a way that I had previously thought was inane) such that we were able to restore our files and continue on observing.

Spectroscopic follow up, principally using the Keck 10 m telescopes through time allocated to Alex Filippenko (through the University of California), and John Tonry (through the University of Hawaii), was scheduled just a few days after our search runs. Failure to quickly identify candidate supernovae meant our discoveries would be effectively useless. Despite the chaos, through 1995–1997, we did manage to discover, spectroscopically confirm, and photometrically follow 16 distant SN Ia—enough to make a statistically robust measurement of the deceleration parameter.

In early 1997, most of the team assembled in Seattle at the University of Washington, and we agreed that each paper would be led by a student or young postdoc from within the group. I would write the first paper where we laid out our program and presented our first object, SN 1995 K. Peter Garnavich was selected to write the next major paper, one that would include objects observed with the Hubble Space Telescope (HST), and would likely tell us our first statistically significant measurement of q_0. And finally, Adam Riess was selected to write the next paper that would refine the value of q_0 based on several years' data. The data grunts of the group (myself, Adam Riess, Pete Challis, Saurabh Jha, Alejandro Clocchiatti, David Reiss, and Al Diercks) stayed on in Seattle to work together for a week. Initially, the week was supposed to be a working bee where I would tutor the group on how to make photometric measurements of distant SN Ia, and we would as a group analyze our data set. While the week did not lead to an analysis of our data set, it instead became an intense workshop where we thought through most of the outstanding issues necessary to complete the experiment. It was one of the most memorable weeks of the High-Z team for me. While Hale-Bopp blazed invisibly above the continual Seattle drizzle, we clocked in 16 h days from the basement of the University of Washington Physics Department—taking a break to all see the movie "Swing Blade" at the request of Adam.

Over the course of the next few years, my life was dominated by SN discovery runs, photometric data reduction, and writing the paper on our SN program and SN 1995 K. The paper was largely complete in 1996, but the ever increasing data load made it challenging for me to finish. In addition, the complication that SN 1995 K was most consistent with negative acceleration made aspects of the analysis challenging. In addition, there were many possible systematic effects that could derail this experiment into giving an incorrect answer, and I was investigating these at this time, one by one.

Systematic Effects: In the nearby universe, we see SN Ia in a variety of environments, and about 10% have significant extinction. Since we can correct for extinction by observing the colors of SN Ia, we can remove any first order effects caused by the average extinction properties of SN Ia changing between $z = 0$ and $z = 0.5$. As part of his thesis, Adam Riess had developed techniques to correct for dust based on the colors of supernovae (Riess, Press, and Kirshner, 1996). This was essential work to accurately measure the relative distances to SN Ia, and is an essential ingredient in all supernova distance measuring techniques today.

Our supernova discoveries suffer from a variety of selection effects, both in our nearby and distant searches. The most significant effect is Malmquist bias—a selection effect which leads magnitude limited searches finding brighter than average objects near their brightness limit. This bias is caused by the larger volume in which brighter objects can be discovered compared to their fainter counterparts. Malmquist bias errors are proportional to the square of the intrinsic dispersion of the distance method, and because SN Ia are such accurate distance indicators, these errors are quite small—approximately 2%. In 1995, I developed Monte Carlo simulations to estimate these effects, and remove their effects from our data sets.

As SN are observed at larger and larger redshifts, their light is shifted to longer wavelengths. Since astronomical observations are normally made in fixed bandpasses on Earth, corrections need to be made to account for the differences caused by the spectrum of a SN Ia shifting within these bandpasses. The SCP had showed that these effects can be minimized if one does not stick with a single bandpass for nearby and distant objects, but by instead choosing the closest bandpass to the redshifted rest-frame bandpass (Kim, Goobar, and Perlmutter, 1996). The High-Z SN search took this one step further, designing new bandpasses, specifically made to emulate the $z = 0$ bandpass at several redshifts.

SN Ia are seen to evolve in the nearby universe. The Calan/Tololo survey plotted the shape of the SN light curves against the type of host galaxy (Hamuy *et al.*, 1996). Early hosts (ones without recent star formation) consistently show light curves which evolve more quickly than those objects which occur in late-type hosts (objects with on-going star formation). This could be a terminal problem for using SN Ia to measure q_0 if it were not for the observation that once corrected for light curve shape, the corrected luminosity shows a much smaller correlation as a function of the characteristics of the host.

Cosmology Beyond Normal Matter: Since 1917, when Einstein first added the cosmological constant to his equations, this fudge factor had been trotted out on several occasions to explain observations of the Universe that did not conform to the standard model described earlier. The cosmological constant had developed a bad reputation as being incorrectly asserted as the solution to what were ultimately found to be bad observations.

In 1995, I had served as the referee of a paper by Goodbar and Perlmutter (Goobar and Perlmutter, 1995) exploring if the meaningful limits on the value of the cosmological constant could be made by high redshift SN Ia measurements. In my referee report I expressed concern of the relevance of the paper—I felt that the paper failed to demonstrate that a meaningful limit could be made on the cosmological constant. If there was no cosmological constant, then the uncertainty in a SN Ia-based measurement would be sufficiently large as not to be interesting (see their Fig. 2). I had failed to grasp—so strong were my priors against a cosmological constant—that if there was a cosmological constant (see their Fig. 3), that a meaningful measurement could be made.

The cosmological constant was not new to me. Sean Carroll had written a review on the topic in 1992, while we shared an office during graduate school (Carroll, Press, and Turner, 1992). I remember that as he worked through hundreds of yellow post-it notes scrawled on his manuscript by his referee, Allan Sandage, I teased him about writing about something as ridiculous as the cosmological constant. This review ended up being extremely useful as I came to grips with how to interpret SN 1995 K, and the range of negative q_0 values it implied.

As part of my paper describing the High-Z SN search (Schmidt *et al.*, 1998), the team theorist, Craig Hogan, encouraged me to go beyond the notion of q_0. He was particularly interested in breaking the assumption that the Universe was made up of only normal matter, postulating that it could be composed of other things as well. In our paper, we adapted our measurement to the standards of particle astrophysics. That is, we adapted the Friedmann Eq. (2) to reflect all species of matter

$$H^2 \equiv \left(\frac{a}{a}\right)^2 = \frac{8\pi G\rho_{\rm tot}}{3} - \frac{k}{a^2} \tag{9}$$

describing each species of matter by their fraction of the critical density,

$$\Omega_i = \frac{\rho_i}{\rho_{\rm crit}} \equiv \frac{\rho_i}{(3H_0^2/8\pi G)}, \tag{10}$$

and this matter's equation of state,

$$w_i = \frac{P_i}{\rho_i c^2}. \tag{11}$$

The equation of state for normal matter is $w = 0$, the cosmological constant, $w = -1$, and photons $w = 1/3$. This formulation made for a less trivial expression for the luminosity distance,

$$D_L H_0 = c(1+z)\Omega_k^{-1/2} S\left\{\Omega_k^{1/2}\int_0^z dz'\left[\Omega_k(1+z')^2 + \sum_i (1+z')^{3+3w_i}\right]^{-1/2}\right\}, \tag{12}$$

where $S(x) = \sin(x)$, x, or $\sinh(x)$ for closed, flat, and open models, respectively, and Ω_k the curvature parameter, is defined as $\Omega_k \equiv 1 - \Sigma_i\Omega_i$. With multiple forms of matter, Mattig's formulation for D_L [Eq. (8)], is no longer valid, but the q_0 expansion, Eq. (6) is still valid, except that q_0 is given by the expression

$$q_0 \equiv \frac{-a(t_0)a(t_0)}{a^2(t_0)} = \frac{1}{2}\sum_i \Omega_i(1+3w_i). \tag{13}$$

The Discovery of Acceleration: By the middle of 1997, the High-Z team had HST observations of 4 objects, and 10 more distant objects to tackle our ultimate goal, measuring q_0. But there were some complications that needed to be sorted out dealing with statistics. In principal, measuring q_0 from several SN distances and redshifts is straightforward. The redshifts have negligible uncertainty, and the distance estimates had distances with uncertainties well described by a normal distribution. A classic χ^2 method seemed entirely appropriate. Except our data were in a part of parameter space where Mattig's exact formula [Eq. (8)] was invalid, and at a redshift where the Taylor expansion solution (5) was not very accurate. On the other hand, Eq. (12) covered all possibilities, but there were regions of parameter space which were not allowed, like negative matter. In discussions at CTIO with members of the SCP in 1996, it became clear that we were both grappling with how to deal with these statistical issues—it was not that they had not been solved by science, it was just that we were in new territory for us, and we were struggling to figure out a solution. Adam Riess, who had become adept at statistics in his thesis, in discussions with Bill Press, came up with the solution of converting χ^2 to a probability, applying priors to this probability space (e.g., no negative matter), and integrating over this space to find the probability distribution for the parameters of interest. It seems so passé now, but in 1996, none of us had ever seen this technique used before in astronomy. Computationally, this was not trivial, and Adam Riess, Peter Garnavich, and I all wrote our own versions of codes that did these calculations.

The HST data that Peter Garnavich was analyzing were of very high quality, and were consequently the easiest to reduce. By September he had finished his analysis—the data clearly showed $q_0 \neq 0.5$, a flat universe composed of normal matter was ruled out—but this seemed at odds with a paper put out by the SCP at this same time (Perlmutter *et al.*, 1997). Peter's draft created a range of reactions within the team—what were our control's on systematic errors, and how could we demonstrate the result was robust? This lead us into examining all sorts of possible systematic errors, and while we never quite reached agreement (Chris Stubbs, who had a particle physics background, was particularly critical of our ability to control all errors) it did mean the team had already grappled with this issue when things got substantially more interesting a few months later. My wife and I had just had our second child, and I have to admit to not doing a good job at getting the team to work together constructively around these issues.

In November of 1997, Adam Riess had finished his first pass at measuring his collection of supernovae—a feat that was achieved due to his unique ability to focus on this one thing with all of his might. He sent me a figure which a subject line of, "what do you think?" I looked at the figure and it showed that his group of SN Ia were, on average, definitively fainter than even a $q_0 = 0$ model. The Universe seemed to be accelerating. I remember thinking, "What has Adam done?" and thus opened up an intense exchange between the two of us, checking the result, and refining the analysis. At the same time, I was working to submit my paper, which I swore would be submitted in 1997—just managing to get it in before New Year's Eve. Finally, on the 8th of January 1998 (Australian Time), Adam and I agreed on all details of the calculation that showed that the Universe was accelerating, and I sent him an email with ''Hello Lambda'' as the subject line, and a figure of my calculations. Most of the High-Z team had not been shown the analysis at this point. Adam had shown his work to Alex Filippenko, and we told Peter Garnavich, who was presenting his paper, described above, at the American Astronomical Society Meeting, the next day.

The result was perplexing to me, the cosmological constant had a long history of being proposed to explain a set of observations which was later on shown to be fatally flawed. And then there were the results of the other team. The 1997 SCP paper was at such odds to what we are seeing, I felt no one would take us seriously with such a crazy result. What I had not seen was the SCP's new paper which appeared on the 17th of December on the astrophysics archive—only learning about it after the AAS press conference on January 8th (Perlmutter *et al.*, 1998). This paper indicated that their value of q_0 was much lower than they had previously presented.

On January 9th, I came into work to get a report of the AAS press conference from Peter Garnavich. In addition to presenting his HST data from his *Nature* paper showing the Universe was not decelerating quickly, Saul Perlmutter had given the audience a peak of his entire collection of 40 objects—and these objects *did* seem to be showing the same thing that we were seeing. Saul's objects were systematically fainter than could be explained in a universe composed only of normal matter. But Saul's team had not yet corrected for dust, a correction that was built into our analysis from the beginning. Adam had chosen this week to get married, and when he returned from a short honeymoon, we had a lot of explaining to do to the team, recounting all of the steps in our analysis. The team's reactions were mixed—some were excited, others were in disbelief, and still others felt that we had a long way to go to show the result to be robust to errors. While I shared in the skepticism, I also felt that it would be wrong not to publish a result just because we did not like it. I challenged the team to suggest tests that they felt needed to be made before we published. Over the remainder of January and February, under Adam's leadership, the team worked through all of the tests requested, such that by the end of February, the team had agreed to the contents of the paper, and we were ready to announce our result. Alex Filippenko presented our team's work at a meeting in California at the end of February, and it created a media sensation in the United States. Our paper was submitted a week later to the Astronomical Journal, ''Observational Evidence for a Cosmological Constant and an Accelerating Universe.'' Over the next few months, in addition to continuing our punishing program of SN observations, Peter Garnavich did the first analysis to show that whatever was

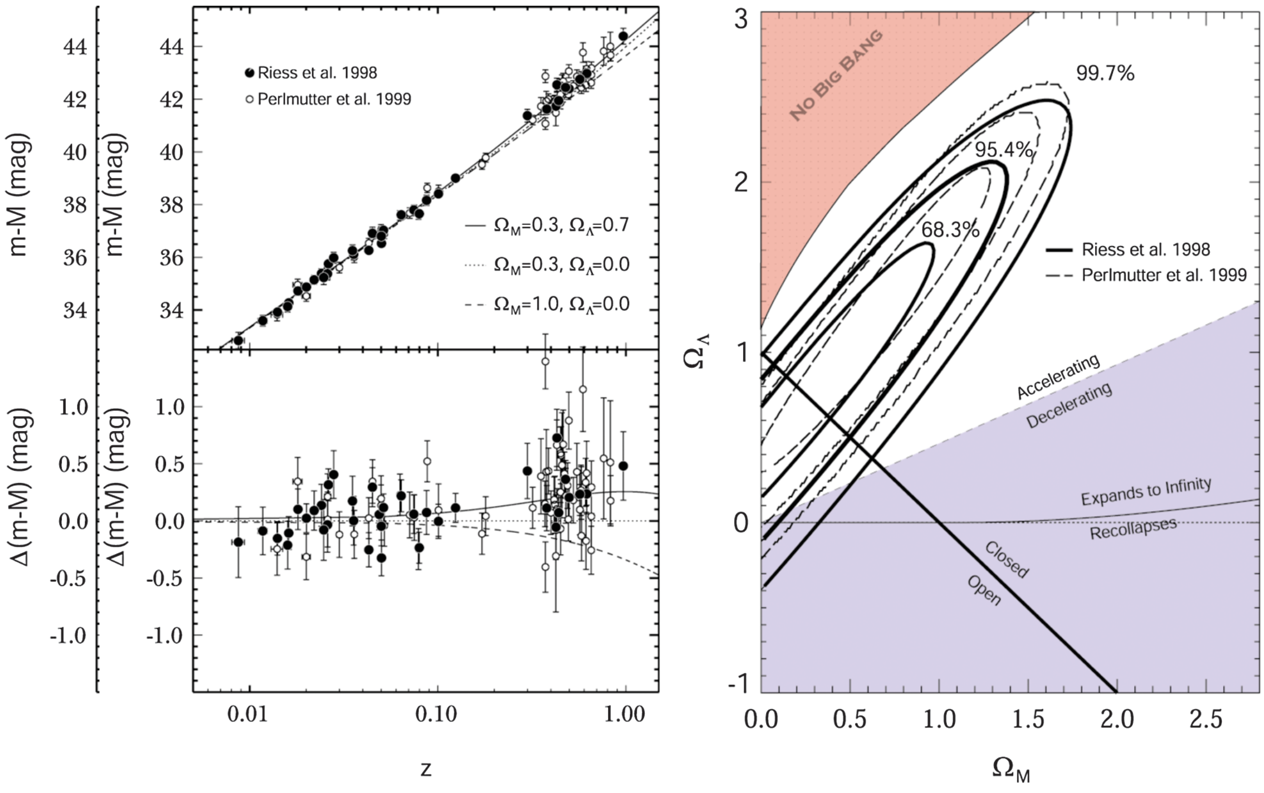

FIG. 7 (color). (a) (left): Top panel: Hubble diagrams of SN Ia showing the High-Z team and SCP data, with 3 sets of cosmological parameters. Bottom panel: Data from the top panel with the model of containing normal matter (30% of the critical density) subtracted. (b) (right): Probability contours for cosmological fits to the SCP and High-Z teams' data. The results from the two projects show remarkable consistency in their conclusion that the Universe has a significant matter component consistent with the equation of state of a cosmological constant.

causing the acceleration, it seemed to have an equation of state, a lot like the cosmological constant.

While I felt that we had done all that was possible with our supernovae to understand our uncertainties, I could not help worrying that something unexpected would turn up, and nullify our results. In the language of a U.S. Secretary of Defense, we had controlled the known unknowns, but there were always the unknown unknowns—and this was a crazy result. I expected the community to be skeptical, and most probably scathing in the assessment of our results.

During this time, the SCP was working frenetically on their own paper—it soon emerged that the conclusions of the two independent experiments were virtually identical (Perlmutter *et al.*, 1999). Their experiment had more objects than ours, but less signal per object—in the end the overall significance of the two experiments was about the same. If combined, the two experiments achieved more than 4σ detection of acceleration (Fig. 7).

To my surprise, the accelerating Universe was received with a warmer reception than what I was expecting. The positive reception was due, I believe, partially to the fact that two highly competitive teams arrived independently to the same answer. But the discovery also provided a solution to some major failings of the prevailing cold dark matter model (CDM)—a model in which initial conditions were set by a period of inflation (Guth, 1981). This model predicted a geometrically flat universe with a distribution of initial fluctuations described as a nearly-scale-invariant Gaussian random field. CDM was in conflict with the distribution of galaxies on large scales, as were the prevailing combination of measurements of the Hubble constant, matter density, and age of the Universe. It was realized that the addition of a cosmological constant could fix all of these problems (Efstathiou, Sutherland, and Maddox, 1990; Krauss and Turner, 1995; and Ostriker and Steinhardt, 1995).

In 2000, the MAXIMA and Boomerang experiments made measurements of the cosmic microwave background which demonstrated that the Universe was flat to within 10%—i.e., $\Omega_k \sim 0$ in Eq. (10) (Hanany *et al.*, 2000 and Bernardis *et al.*, 2000). This measurement was essentially impossible to reconcile with our supernova distances unless the Universe was full of something like a cosmological constant. It was at that moment in 2000 that I finally felt secure that our findings would stand the test of time.

Concluding Remarks: In the 13 years since the discovery, the accelerating cosmos has received intense scrutiny throughout physics. On the observational side, increasingly large samples of type Ia supernovae have improved the precision of the measurements of acceleration to the point where they are now systematically, rather than statistically limited (Wood-Vasey, 2007; Hicken *et al.*, 2009; Kessler *et al.*, 2009; and Guy *et al.*, 2010).

Measurements of the cosmic microwave background have established an increasingly precise measurement of the angular size distance to a redshift of approximately $z \sim 1090$, as well as the physical conditions of the Universe from just after the big bang through to the time of recombination (Komatsu *et al.*, 2011). The scale of Baryon acoustic Oscillations, whose size are understood through modeling of the cosmic microwave background, have been traced over time through their imprint into the population of galaxies. Astronomy can now connect the scale of the Universe from $z \sim 1080$ to $z = 0.2$ (Percival *et al.*, 2010), $z = 0.35$ (Eisenstein *et al.*, 2005), and $z = 0.6$ (Blake, 2011). Together, the measurements listed above, and most others, remain consistent with a universe where the acceleration is caused by Einstein's cosmological constant ($\Omega_\Lambda \sim 0.73$, $w = -1$), the Universe is geometrically flat, and the remainder of the matter is dominated by pressureless ($w = 0$) matter (Sullivan, 2011), split between baryons ($\Omega_B \sim 0.045$) and cold dark matter ($\Omega_{\mathrm{CDM}} \sim 0.225$). This basic model is often described as the flat Λ-CDM model.

An enormous body of theoretical work has been undertaken in response to the discovery of the accelerating Universe. Unfortunately, no obvious breakthrough in our understanding has yet occurred—cosmic acceleration remains the same mystery that it was in 1998. The future will see bigger and better experiments that will increasingly test consistency of our Universe with the flat Λ-CDM model. If a difference were to emerge, thereby disproving a cosmological constant as the source of acceleration, it would provide theorists with a new observational signature of the source of the acceleration. Short of seeing an observational difference emerge, we will need to wait for a theoretical revelation that can explain the standard model, perhaps informed by a piece of information from an unexpected source.

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