

Edmund Bertschinger

Southern Skies and Cosmic Questions

How big is the observable universe?

What is it made of?

Why does space repel itself?



In January 2006—the middle of summer in the Southern hemisphere—a bus full of MIT alumni, family, and friends ascended a narrow, winding dirt road through the coastal range of Chile up to 2400 meters (8000 feet) elevation. After visiting European and American national observatory sites during the preceding days, the group was eager to see the private observatory of which MIT is a partner: the Magellan Telescopes at Las Campanas Observatory. Only one traveler in the group had been there before: five years earlier, Jane Pappalardo had attended the dedication of the newly built telescopes. The author, serving as a scientific tour guide, was excited to arrive finally at the facility his colleague, MIT Magellan director Prof. Paul Schechter, had helped design and commission. After traveling a week through Northern Chile we had reached the summit of a remarkable trip.

CHILE—A THIN STRIP OF LAND between the Pacific Ocean and the crest of the Andes—is an astronomical mecca. The cold Humboldt ocean current flowing northward from Antarctica keeps the marine clouds low against the wall of coastal mountains. To the east, the Andes are high enough to block most of the



FIGURE 1
Wide-angle view of the Southern sky taken from the Andes Mountains of Argentina on January 28, 2007. Visible are Comet McNaught, the brightest comet in over 40 years; the splotchy Milky Way; and our two satellite galaxies, the Magellanic Clouds. (Photo credit and copyright: Miloslav Druckmüller)

FIGURE 2

The octagonal “domes” of the twin Magellan Telescopes at Las Campanas Observatory, Chile. The Science Support Facility, named after donors Cecil and Ida Green and Jane and Neil Pappalardo, lies downhill. (Photo credit: Dave Hadley)



moisture from the Amazon rain forest. As a result, northern Chile is home to the driest desert in the world—the Atacama—and has the clearest readily accessible skies. Chile takes advantage of this natural resource to host several international astronomical observatories in exchange for a 10% share of observing time on the telescopes. It is also beginning to host a small but growing trade of astro-tourism. Our tour, organized by the MIT Alumni Travel Program, was called “The Skies of the Southern Hemisphere: Chile & the Magellan Project.”

The Magellan Project is operated by a consortium of private universities (Harvard, MIT, Michigan, and the University of Arizona) plus the Carnegie Institution of Washington. The consortium built and operates the Magellan Telescopes that produce, without adaptive optics correction, among the best optical images on earth. (The Hubble Space Telescope does better above the atmosphere.) After viewing two days earlier the lavish facilities at the European Paranal Observatory (including an astronomers’ “dormitory” with an indoor swimming pool), the MIT travelers were eager to see the facilities of the “lean and mean” Magellan Project.

At the observatory we were warmly greeted by Magellan Site Manager Frank Perez, who showed us the telescopes, as well as the mirror resurfacing facility (where the mirrors are cleaned and a thin film of aluminum is reapplied every two years), and some of the complex instruments that analyze the light collected by



FIGURE 3

Close-up of one of the Magellan telescopes. The 6.5m-diameter primary mirror lies inside a white mirror cell at the bottom; the much smaller secondary mirror lies at the top. Like other “new technology” telescopes, Magellan has a short squat design, a lightweight frame, and a low mass enclosure to minimize heat capacity. It also uses extensive air conditioning to keep all parts of the telescope at ambient nighttime temperature. As a result, there is no accumulated heat to “boil off” when the enclosure opens in the evening, so images are steady. Half of the time, the recorded image size of a point source is less than 0.6 arcseconds, the size of a mosquito at 2 miles. (Photo credit: L. Robert Johnson)

the big telescopes. (The last time an eyepiece was put on one of the big telescopes was during the dedication ceremony.) Frank explained how the electronic guider sensed gradual changes in the mirror shape during observations and automatically applied forces to keep the mirror in the right shape, using the technology developed by Prof. Paul Schechter.

Time Machines

As impressive as modern telescopes are for their high technology, it is their scientific output that most excites astronomers. At Magellan we were fortunate to be met by MIT astronomer Rob Simcoe, then a Pappalardo Postdoctoral Fellow and now an Assistant Professor of Physics at MIT, who showed the group his chemical analysis of gas clouds tens of billions of light years from Earth. How could he see so far, and what do his results teach us? [Author’s note: a challenge to challenge to the reader: explain how light can travel more than 40 billion light years in a time of less than 13.7 billion years, the age of our observable universe. The answer will be given at the end of this article.]

Telescopes are time machines. It takes light eight minutes to travel to us from the sun, four years to reach us from the next nearest star, and more than ten billion years to arrive from the quasars observed by Dr. Simcoe. A quasar is a tremendously

Cosmological Redshift of Quasar Spectra

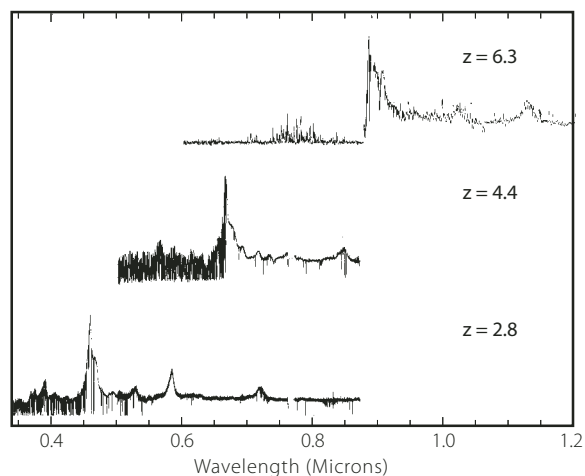


FIGURE 4

Rob Simcoe showed the travelers his spectra of distant quasars. The middle spectrum, with a redshift $z=4.4$, was taken in 2006 the night before we visited the observatory. The dark portions of each spectrum provide cosmic core samples through the universe tens of billions of light years long. (Credit: Robert Simcoe/MIT)

bright light source existing in the centers of some distant galaxies. A quasar's power comes from the gravitational potential energy released as gas spirals into a giant black hole. While quasars are intrinsically fascinating objects, they are also a powerful tool for chemical analysis of gas within or between other galaxies anywhere along the line of sight to the quasar.

Hydrogen, carbon, and other chemical elements absorb light of distinct frequencies as it moves from the source to us, creating narrow dark regions in the quasar spectrum. The wavelengths of these dark regions are shifted by the expansion of the universe in such a way that astronomers can determine where and when the quasar light was absorbed. Using the Magellan Telescopes, Dr.

Simcoe measured the rate of increase of carbon in the universe as it was produced in stars which pollute their surroundings. He found that the cosmological buildup of carbon was gradual over the last ten billion years and rapid before then. Would that the same were true for carbon in the Earth's atmosphere!

Comet of a Lifetime

The success of our first alumni tour to Chile, in 2006, inspired its imitation by several other universities including Yale, whose travel brochure featured the photography of MIT alumnus and Physics Visiting Committee member Bob Johnson. Of course we had to return to Chile to do better than the competition. One year later, our timing couldn't have been better. The second MIT alumni tour of the Southern skies arrived in the Atacama Desert just after Comet C/2006 P1 McNaught passed closest to the sun in mid-January 2007. We first spotted the

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FIGURE 5

Chilean adventure tour leader Prof. Ed Bertschinger and longstanding Department friend Jane Pappalardo in front of the twin Magellan Telescopes.



Two Short Lectures on Astrophysics

by Dr. Edmund Bertschinger

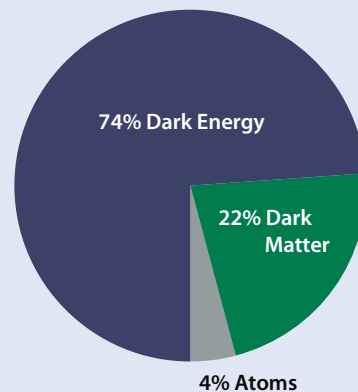
Visits to the natural and archaeological wonders of the Atacama during the alumni trip were interspersed with my lectures on astrophysics, which were enjoyed with pisco sours. I am a theoretical astrophysicist; most of my research conducted in the MIT Kavli Institute for Astrophysics and Space Research has focused on trying to understand what 96% of the universe is made of and how it behaves. Atoms and their constituents comprise only 4% of the universe today!

DARK MATTER

Dark matter is the nondescript name given to the diffuse material providing most of the mass of galaxies and playing a key role in galaxy formation. Its existence—deduced from the absence of sufficient mass contained in visible stars and gas to keep galaxies in their observed orbits—was first proposed in the 1930s. The successful prediction of new matter from its unseen gravity is not unprecedented; in the 1840s the eighth planet, Neptune, was deduced and then found from irregularities in the orbit of Uranus.

The irregularities in galactic orbits produced by dark matter are far more dramatic than the minor perturbations in the solar system. Our galaxy, the local group of galaxies, and all galaxy clusters would fly apart—indeed, they would not even have been assembled after the big bang—without far more gravitating mass than is seen. Unlike Neptune, though, the cosmic dark matter has not yet been seen by any measurements except the effects of its gravity. However, a panoply of indirect arguments show conclusively that the dark matter cannot be made of atoms or known particles. The most plausible explanation for dark matter is a new elementary particle generically called a “weakly interacting massive particle” or WIMP. WIMPs are being searched for by the very rare collisions they have with atoms in terrestrial laboratories, including those of MIT physics faculty Enectali Figueroa-Feliciano and Peter Fisher and Pappalardo Fellow Jocelyn Monroe.

The properties of galaxies like our own Milky Way give us important clues to the nature of dark matter, since galaxies formed as a result of gravitational condensation out of the expanding remnants of the big bang and most of the gravi-



Approximate composition of the universe today, by fraction of mass-energy of the total. Neutrinos, photons, and other known particles contribute less than 1%. “Dark” means “unseen by all measurements except gravity.” Dark energy and dark matter have different gravitational effects. (Image credit: NASA/WMAP Science Team)

tating mass is dark matter. (Dark energy, as we shall see, is very different and plays little role, if any, in galaxy formation.) Despite the complexity of galaxy formation and evolution, the observed properties of galaxies point to several firm conclusions about dark matter. In particular, dark matter particles must be so small (as measured by their cross sections for elastic and inelastic collisions) as to be nearly collisionless. A cloud of dark matter particles would easily pass through the earth, the sun, or another dark matter cloud. Colliding atomic gas clouds, by contrast, are shock heated and cool by emission of photons. Add gravity, and the result of heat loss to photons is to compress to higher density, concentrating atoms into dense objects—stars and planets—while dark matter remains diffuse. The average density of dark matter in the universe today is about 2 milligrams in a volume equal to that of Earth. The local value in our galaxy is approximately one million times higher, still a better vacuum than interplanetary space.

The very existence of galaxies implies that the clouds of dark matter particles which seeded galaxy formation must have been very cold, otherwise thermal motions of the particles would have dispersed the clouds before galaxies could form. This realization led to the exclusion of neutrinos as dark matter in the 1980s: neutrinos born in the fires of the big bang are too “hot” to allow galaxy formation if they were the dark matter. The most popular candidate for dark matter today is a hypothetical “cold” WIMP called the neutralino. Like the neutrino, the neutralino rarely collides with anything. However, the neutralino, if it exists, must be much heavier than the neutrino, hence its temperature decreases much faster with cosmic expansion. If the neutralino weighs one hundred times as much as a proton (a plausible value), then the dark matter in intergalactic space today is predicted to have a temperature of about 20 picokelvin, more than 20 times colder than the temperatures reached in the Bose-Einstein condensates created by Prof. Wolfgang Ketterle.

My own studies of dark matter aim at a detailed theoretical understanding of dynamics starting from the early universe and going forward in time until galaxies form. Interestingly, the hardest questions involve the simplest physics: Newton’s laws of motion and the inverse square law of gravity. A self-gravitating gas of cold dark matter particles develops turbulence owing to the nonlinear interaction of structures of many different sizes. This turbulence is more complicated than the wake of an airplane or boat because, unlike an ordinary fluid, dark matter is collisionless.

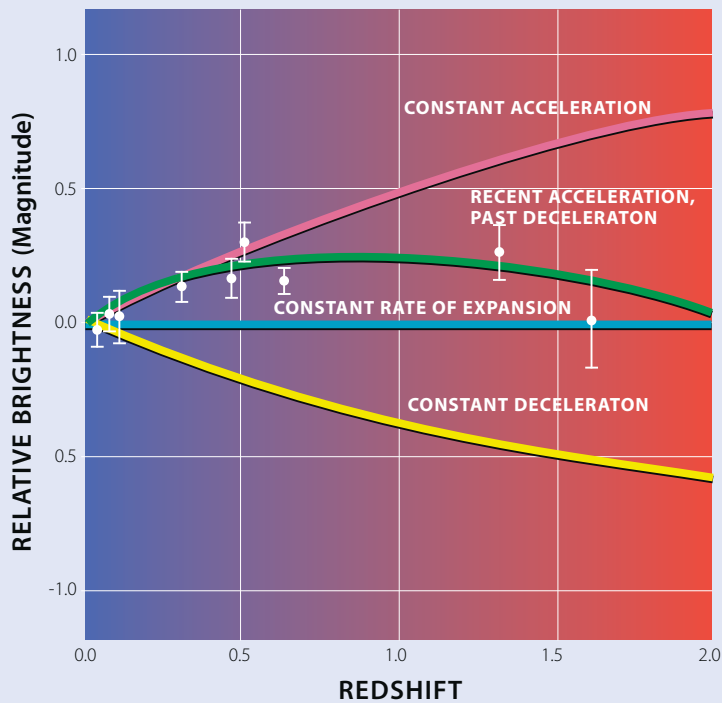
Most research on galaxy formation use large numerical simulations, while my research emphasizes the complementary approach of analytical techniques solving mathematical equations. One result is a prediction that the dark matter should exhibit very high density surfaces, called caustics, which are a three-dimensional analogue of the bright lines of light seen on the bottom of a swimming pool. These caustics—as well as the small dark matter clouds predicted to rain onto galaxies—would have little effect on galactic structure but they might affect experimental searches for dark matter particles or their annihilation products. Conversely, detection of dark matter may one day test our models of collisionless turbulence.

DARK ENERGY

Four percent of our universe is atoms, which make up everything we are and can see; twenty-two percent is dark matter. The remaining 74% is dark energy. Dark energy is the name given to attempts to explain a stunning discovery announced in 1998 by two teams of astronomers. Instead of slowing down from the gravitational attraction of everything to everything else, the expansion of the universe is accelerating. It’s as if one were to toss a ball up in the air and gravity, instead of pulling it back to earth, pushes it ever faster and further into deep space. Apparently, if you could take a ball out to a distance of a few hundred million light years, this is exactly what would happen!

Statistically, the strongest evidence for dark energy comes from measurements of cosmic expansion inferred from supernova explosions seen across the visible universe. Measurements of distance and redshift (the amount by which the universe has expanded since the light was emitted) can be combined to give the expansion history of the universe, and therefore measure whether the expansion is accelerating or decelerating. The so-called Type Ia supernova provides the standard signal by which distance is indirectly measured: a carbon-oxygen white dwarf star—the cold, dead remains of a star somewhat more massive than our sun—slowly steals mass from a binary companion until the white dwarf exceeds the maximum stable mass worked out by Chandrasekhar in the 1930s, leading to a huge supernova explosion which emits a flash of light similar in size for all Type Ia supernovae. By combining the calibrated optical emission of these explosions with their brightness observed on Earth, astronomers can infer the distance. Years of intense scrutiny have only strengthened the conclusions drawn a decade ago: Type Ia supernovae tell us that something is causing the universe to accelerate. Almost all we “know” about this something is the name cosmologists have given it: dark energy.

Despite their names, dark energy and dark matter have, we think, only two things in common. First, the only evidence for their existence comes to date from their gravitational effects. Second, the evidence for both is so strong, and involves such an interlocking web of different measurements, that the simplest hypothesis consistent with the data is that both dark substances exist. Of the two, dark energy is harder to study because it appears to play no role in galaxy formation, nor



Supernova brightness reveals the distance in light-years; redshift reveals the expansion of the universe. Measurement of both quantities allows astronomers to deduce the expansion history of the universe. For unknown reasons, the universe began to speed up about 5 billion years ago. (Image credit: Adam Riess, Johns Hopkins University).

does it concentrate in galaxies. Something causes distant galaxies to repel each other while nearby ones attract. Dark energy behaves like a virus that has taken over the cellular machinery of space, forcing it to grow without limit.

In what sense can one call dark energy a substance? Dark energy might be a gravitating substance, albeit with a repulsive rather than attractive force. Paradoxically, empty space itself—a vacuum—may be the answer to the dark energy puzzle. According to quantum physics, the vacuum is an active environment full of “virtual” particles and antiparticles that materialize and live briefly on time borrowed from the Heisenberg Uncertainty Principle before disappearing again. While not a substance one can hold in one’s hand, this sea of fluctuating virtual particles causes gravity. (Light also causes gravity and is difficult to hold in one’s hand.) In the 1960s it was realized that vacuum quantum fluctuations correspond to a substance with positive energy and negative pressure, and that negative pressure causes repulsive gravity accord-

ing to general relativity. The effect is the same as the repulsive gravity term Einstein introduced in 1917, when he realized that his field equations would not permit the universe to be static in the presence of ordinary matter, as he then thought it was. Einstein’s cosmological constant was, by assumption, just strong enough to counteract the mutual gravitational attraction of matter. Today’s dark energy is several times stronger. Einstein’s self-described greatest blunder—the cosmological constant—may yet be correct, if made a little stronger.

Unfortunately, theoretical estimates of the vacuum energy show that, unless some extraordinary cancellation occurs, dark energy should be up to 123 orders of magnitude, that is 10^{123} times, as strong as is observed. This “cosmological constant problem” remains a great challenge to physicists.

Instead of vacuum energy, dark energy might be an exotic form of mass-energy called a slowly rolling scalar field. This idea has traction: the same mechanism was invoked by Professor Alan Guth to drive a phase of accelerating expansion in the very early universe. His inflationary universe model resolves many of the puzzles of the big bang theory, especially those related to the large-scale uniformity of the visible universe and the small fluctuations that give birth to galaxies. However, it seems bizarre that the universe would begin another phase of inflation around the time our sun was born. That is very late in the universe by the standards of particle physics.

A third possibility is that dark energy is not a substance at all, but instead arises due to modifications of Einstein’s theory of general relativity. This possibility is subtle because the measurements of dark energy made to date assume that general relativity is exact. I’ve been studying ways to test modified gravity theories that add one free parameter to general relativity. The approach is similar to what has been done to test general relativity in the solar system. By combining various measurements of light as well as motions of galaxies, it should be possible to determine whether dark energy is a substance or modified gravity. Understanding dark energy is a major goal of cosmology research for the next decade—if not the next century!

FIGURE 6

Comet McNaught photographed in the twilight above Lunar Valley near San Pedro de Atacama, January 16, 2007. (Photo credit: Dave Hadley)



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comet just above the horizon about 45 minutes after sunset on our first evening in the Atacama Desert. With spotting scope, binoculars, and averted vision we saw a thrilling tail. For several travelers, it was their first comet. For all of us it was the best.

Comet McNaught came from the Oort cloud of comets far beyond Neptune (not to mention beyond the dwarf planets like Pluto), on an orbit nearly at right angles to the plane of Earth's orbit. After passing the sun it was visible only in the southern hemisphere. I cautiously opined to the group that McNaught should be visible for several more days and might appear brighter as it moved farther from the sun and was visible longer after sunset. However, nothing prepared us for the incredible tail shown in *Figure 1*. Several of us saw a view like this (albeit after the comet nucleus had set) from the amateur Collowara Observatory in the mountains above La Serena.

A bright early evening comet is every amateur astronomer's dream. At the end of a fabulous dinner in Calama, I told the group that we had prepared a special treat after dessert. Armed with sweaters and binoculars, we convened onto the hotel steps to watch the awesome harbinger of an unforgettable trip. When I exclaimed excitedly, "This is the comet of a lifetime!" one of the group members replied, "Comet? This is the *trip* of a lifetime!"

The nighttime sky in Chile even without, but especially with, a bright comet, is breathtaking. In one viewing that evening, we saw a comet or planets ten light minutes distant, the nearest star outside our solar system some five orders of magnitude (one hundred thousand times) further away (Alpha Centauri, four light years), and the nearest galaxies, approximately another five orders of magnitude beyond (the Magellanic Clouds). One more step with this multiplier covers the entire observable universe!

But it isn't enough to see the pictures—I stood silently beneath a star-spangled wide-open sky to soak in the grandeur of the cosmos. I felt in my heart the neutrinos coming from distant supernovae, like those measured on the earth 20 years ago when Supernova 1987A blazed in the Large Magellanic Cloud. I waved at the nearby stars Beta Pictoris and Epsilon Eridani, whose orbiting disks of dusty debris almost certainly harbor young planets. Somewhere, perhaps, others were waving back at us. Sharing this elation of the skies with alumni, their family, and friends is one of the greatest pleasures of my life.

MIT Alumni and the Spice of Life

Each of the two MIT alumni tours to Chile included an optional extension. In 2006, the first group visited the southern lakes region of Chile, a lush area of Chile reminiscent of Bavaria. In 2007 the second group visited Easter Island, an



FIGURE 7

*Pondering our past and future:
MIT alumni travelers at Ahu Tongariki,
Easter Island, 2007. (Photo credit:
John Isaacson)*

archaeological treasure in the middle of the Pacific Ocean. Having read Jared Diamond's *Collapse* before the trip, I found the famous stone statues haunting, and the metaphor for the fragility of the Earth's ecosystem unsettling.

MIT alumni are remarkable and delightful. In 2006, when our bus driver got lost driving to Paranal Observatory, Howard Messing pulled out his handheld GPS receiver, Bob Johnson pulled out a good map, and together we charted the correct route. The 2006 alumni group also suggested a tour of the Large Hadron Collider at CERN, the European laboratory for particle physics in Geneva, Switzerland. Institute Professor Emeritus Jerry Friedman led a special tour of this laboratory in May 2007, showing the alumni the enormous particle detectors which soon will

be sealed up to measure the highest-energy collisions of protons and ions produced on earth.

For the 2007 trip, alumna Nancy Pottish invited her friend and postgraduate employer Bob Jones, who was a senior engineer at Perkin-Elmer during the construction of the Hubble Space Telescope. Bob gave us a personal account of the infamous “spherical aberration” error in the polishing of the Hubble mirror when two employees tried to outsmart the system. His guest lecture and slideshow were a wonderful addition to our program.

One of the greatest thrills of traveling with an MIT alumni group is the likelihood that whatever we do, the group will have expertise. In the Atacama Desert, Paul Todd taught us about extremophiles—life such as sulfur-eating bacteria living in the El Tatio Geysers—and their interest as a possible form of life on Mars. Geophysicists Dave Hadley and Bob Hart taught us about rift and subduction zones and their importance for the Andes. But the sciences are only part of our interest and expertise. Throughout Chile the group’s birders shared their binoculars, field guides, and excitement with everyone. At the Cousino Palace in Santiago, Ali Moiin taught the Chilean tour director about the lavish Persian carpets as the rest of the group listened in delight.

Alumni trips also remind us how respected MIT is around the world. The Director of Conservation at the Precolumbian Art Museum in Santiago proudly described her collaboration with MIT Materials Science Professor Heather Lechtman, studying the metallurgy of ancient bronze artifacts. Observatory directors spent hours with us and expressed pride in the role MIT played in their facilities.

The 2007 group asked me how I would top their experience for the next trip: Would I, for example, order up a supernova in our galaxy? I ducked that question but the answer is straightforward: MIT alumni will make the trip fascinating, original, and fun. However, for variety we are making one change to the pattern: the next trip to Chile will be in the austral winter, July 21-August 1, 2008 (including an optional extension to Easter Island). Instead of the Magellanic Clouds, we’ll see the magnificent center of our own galaxy overhead. This will increase the chances for a bright supernova!

For information and reservations see alum.mit.edu/lt/travel/calendar/. A travelogue of the Chile trip is online at web.mit.edu/edbert/Chile/. Also watch for future trips to view total solar eclipses in some beautiful places; if anything can top the comet of a lifetime, it’s a total solar eclipse!

Postscript: How Far We Can See

Returning to the author’s challenge question from “Time Machine” on page 35: How can light travel more than 40 billion light years in only 13.7 billion light years? The answer: by surfing on expanding space.

To understand this, follow a light ray backwards in time and outwards in space from the Milky Way to a distant quasar. For simplicity, assume that the expansion of the universe stretches galaxies apart in proportion to the time since the big bang. Divide up the timeline into ten equal parts, each of 1.37 billion light years dura-

tion. Approximate the expansion of the universe as a series of steps: the galaxies begin crushed into a tiny volume, then they are separated by 10% of their present distances, next they are separated by 20% of their present distances, and so on.

During the first increment along the trip backwards in time the light traveled a distance of 1.37 billion light years and, in our approximation, the galaxies remained at their present-day separations.

During the second increment the light traveled another 1.37 billion light years; however, the galaxies were 10% closer to each other then. Consequently, during this interval the light traveled between galaxies which *today* are separated by $1.37/0.90=1.52$ billion light years. Similarly, during the third increment light traveled between galaxies which today are separated by $1.37/0.80=1.71$ billion light years. Repeating the process for a total of 13.7 billion years gives a total distance traveled in billions of light years, as measured by today's galaxy positions, of

$$\left(1.0 + \frac{1.0}{0.9} + \frac{1.0}{0.8} + \frac{1.0}{0.7} + \frac{1.0}{0.6} + \frac{1.0}{0.5} + \frac{1.0}{0.4} + \frac{1.0}{0.3} + \frac{1.0}{0.2} + \frac{1.0}{0.1}\right) \times 1.37 \approx 40.1 \text{ (billion light years)}$$

This estimate can be refined by using calculus and a more accurate expansion history; the actual result is uncertain, but is almost certainly larger than 40 billion light years.

DR. EDMUND BERTSCHINGER is a Professor of Physics, former Division Head of Astrophysics, and, as of January 1, 2008, Department Head of Physics at MIT. He is a theoretical astrophysicist whose research interests focus on cosmology and relativistic astrophysics. A native of California, he received his B.S. in Physics from Caltech in 1979 and his Ph.D. in Astrophysical Sciences from Princeton University in 1984. Following postdoctoral positions at the University of Virginia and at UC-Berkeley, he joined the MIT faculty in 1986, where he rose through the ranks, reaching his present position as full professor in 1996.

Professor Bertschinger is passionate about education. He enjoys teaching classical mechanics, electromagnetism, quantum mechanics, relativity, and cosmology. In collaboration with Dr. Edwin Taylor, he introduced an undergraduate class on black holes and astrophysics that is taken by MIT alumni as well as by undergraduates. In 2002, he received the Physics Department's Buechner Teaching Prize for his undergraduate and graduate classes in relativity.

Professor Bertschinger also loves working with students on research in astrophysics, cosmology, and general relativity. His research students at the high school and undergraduate level have won national prizes for their work, including First Prize in the Intel Science Talent Search. His former Ph.D. students now hold faculty positions at Harvard, Columbia, UC-Berkeley, and other fine universities.

As a member of the MIT Kavli Institute for Astrophysics and Space Research, Prof. Bertschinger leads a research program studying the mysteries of dark energy and dark matter. He and his research students investigate the formation of cosmic structure after the big bang, the physics of dark matter both in the early universe and in forming galaxies, and the physical processes governing matter and radiation close to black holes.