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JOHN NORRIS BAHCALL
1934–2005

A Biographical Memoir by
SCOTT D. TREMAINE

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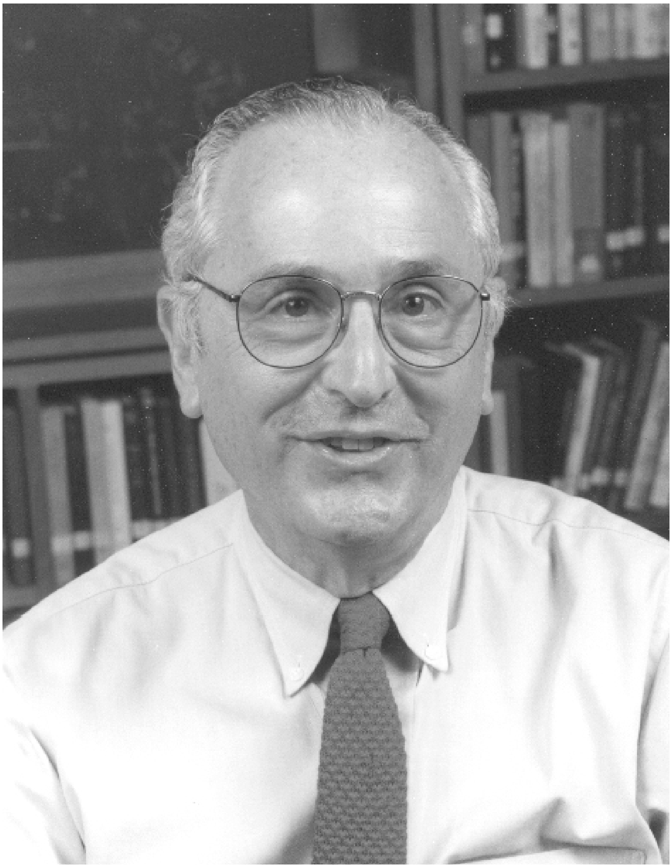
Biographical Memoir



JOHN NORRIS BAHCALL

December 30, 1934–August 17, 2005

BY SCOTT D. TREMAINE

John Bahcall, the Richard Black Professor of Astrophysics at the Institute for Advanced Study, was one of the towering figures of 20th-century astrophysics. His original career goal was to become a rabbi,[1] but he took his first science course late in his undergraduate career, fell in love with physics, and never looked back. His major achievements include precise calculations of the structure of the Sun, which led to the identification and solution of the solar neutrino problem; contributions to a wide range of topics in Galactic and extragalactic astrophysics, including the structure of the intergalactic medium, the distribution of stars in the Galaxy, and the behavior of dense stellar clusters around black holes; a major role in the scientific design and advocacy for the Hubble Space Telescope; leadership of long-range planning for the U.S. research effort in astronomy and astrophysics; the development of the Institute for Advanced Study as one of the world's premier centers for astrophysics; and the mentoring of a significant fraction of today's leading theorists in astrophysics. Any one of these contributions would have been sufficient for a distinguished career.

THE SOLAR NEUTRINO PROBLEM

Almost all of our understanding of the interior of the Sun comes from a handful of observations, for example, its mass and radius; the spectrum of its photosphere; its rotation and magnetic fields; and solar seismology. Yet the energy source for stars like the Sun lies deep in the interior, in a region that is inaccessible to all such observations. Neutrinos emitted in nuclear reactions in the core of the Sun stream freely through the Sun and interplanetary space to Earth; thus the detection of solar neutrinos provides a unique probe of the center of the Sun and the nature of its power source. The difficulty is that neutrinos interact extremely weakly with matter; this of course is what allows them to escape from the Sun but also means that a large and sophisticated detector is needed to measure the neutrino flux from the Sun.[2] Bahcall became interested in this challenging problem as a postdoctoral fellow at Caltech in the early 1960s and began providing theoretical calculations of the expected neutrino luminosity and spectrum to Raymond Davis at Brookhaven National Laboratory, who was planning a large neutrino detector containing 400,000 liters of cleaning fluid, 1500 meters underground in the Homestake Mine in South Dakota. Chlorine nuclei in the cleaning fluid would capture solar neutrinos and be converted to argon atoms, which would periodically be extracted from the tank and counted. The initial estimates were not encouraging, but Bahcall realized in 1964 that transitions to excited states in argon could enhance the neutrino capture cross-section by a factor of about 20, thereby making the experiment practical. Shortly thereafter he published a predicted capture rate of 40 ± 20 SNU (solar neutrino units, or 10^{-36} captures per atom per day, a unit invented by Bahcall) for the Davis experiment; remarkably, although this implied the production of only a few argon atoms per day throughout the tank, Davis was confident that he could reliably detect these. Bahcall's optimistic prediction soon declined to ~ 8 SNU with better understanding of the nuclear physics (Bahcall, Bahcall & Shaviv 1968). It is a tribute to Bahcall's standards that the best estimate at the time of his death almost four decades later, from what proved to be his last scientific paper, was almost unchanged: 6.6-8.1 SNU, depending on the still controversial heavy-element abundance in the Sun.

By 1968 preliminary results from Davis's chlorine experiment yielded an upper limit to the capture rate of 3 SNU. The experiment continued to operate stably for over two decades, gradually reducing its systematic and statistical errors, and the final, definitive capture rate was 2.56 SNU with an uncertainty of about 10 percent. Thus, the observed rate was below Bahcall's predicted rate by about a factor of three. This "solar neutrino problem" was a painful thorn in the side of both neutrino physics and stellar physics for over three decades.

For some time the solar neutrino problem was dismissed as unimportant by the majority of researchers. The attitude of many experimental nuclear physicists was "the experimental results are probably correct, but there must be a problem with the astrophysics," while the attitude of many astrophysicists was "the theoretical calculations are probably correct, and there must be some problem with the experiments" (more briefly, "either Davis or Bahcall is wrong"). Even in the absence of mistakes there were enough uncertainties in the calculations that many theorists argued that the problem would eventually go away. Bahcall never accepted this tempting solution. Over the next several decades many checks were made on both the experimental procedures and the theoretical models, and the solar neutrino problem steadily became more robust. Dozens of modifications to Bahcall's standard solar model were suggested to account for the unexpectedly low neutrino flux—pollution of the solar surface with heavy elements, mixing of the solar interior, errors in the opacities or reaction cross-sections, rapid rotation of the core, strong magnetic fields, and even a black hole at the center of the Sun. Many of these explanations focused on the concern that the neutrinos measured in the Davis experiment came mostly from the decay of boron, a rare reaction channel that produces only about 0.01 percent of the Sun's energy. Bahcall patiently and carefully examined each suggestion, lobbied for new measurements if necessary, and either discarded the proposed effect or incorporated it in his calculations.

It eventually became clear that the only way to make progress was through new experiments; Bahcall was a passionate and effective champion for these and his efforts were remarkably successful. The most important new radiochemical experiments were based on two gallium detectors, which are sensitive to neutrinos from the reaction chain that produces 99 percent of the Sun's energy: the Soviet-American Gallium Experiment (SAGE), which has been operating in the Caucasus mountains of Russia since 1989, and GALLEX, which operated in the Gran Sasso underground laboratory in Italy from 1991 to 1997. These are complemented by experiments that detect neutrino-electron scattering through the Čerenkov radiation emitted by the recoil electrons. These included Kamiokande-II (3000 tons of water) and Super-Kamiokande (50,000 tons of water) in Japan and the Sudbury Neutrino Observatory (1000 tons of heavy water) in Canada. In 1989 Kamiokande-II reported that the neutrino flux from boron decay was less than half of that expected in the standard solar model—the first direct confirmation of Davis's result after more than two decades. Kamiokande-II also verified that the detected neutrinos were indeed coming from the direction of the Sun.

In parallel with these experimental developments, a dramatic theoretical explanation for the solar neutrino problem was emerging. As early as 1969 Pontecorvo and Gribov had pointed out that if neutrinos have nonzero mass, they are expected to oscillate between states or types—more precisely, they are produced in a flavor eigenstate (electron neutrinos) that is not a mass eigenstate, and thus solar neutrinos oscillate after they are created, becoming a mixture of electron, muon, and tau neutrinos. Most neutrino experiments detect only electron neutrinos so if a substantial fraction mix into the muon or tau states during their passage from the solar core to Earth the observed rate will be smaller than expected by as much as a factor of three. This explanation was initially viewed as implausible since complete mixing requires special choices for the "mixing angles" that relate the mass and flavor eigenstates. However, in the 1980s Mikheyev, Smirnov, and Wolfenstein showed that as the neutrinos traverse the Sun they encounter a critical density at which interactions with the solar plasma cause nearly complete flavor transformation (the MSW effect). By 1990 Bahcall was persuaded that neutrino mixing was the likely solution to the solar neutrino problem.

Over the following decade the pieces of the puzzle finally fell into place. First, helioseismology—the measurement of the frequencies of a multitude of small-scale normal modes of the Sun—showed that Bahcall's standard solar model correctly predicted the sound speed throughout most of the Sun to within 0.2 percent, a remarkable achievement and in many ways a more stringent test of our understanding of the solar interior than solar neutrino measurements. This success strongly suggested that the solution to the solar neutrino problem must lie in new physics. Then, in 1998 the Super-Kamiokande collaboration announced evidence for oscillations in neutrinos generated by cosmic rays in the upper atmosphere. This result showed that neutrinos have mass and that they undergo flavor mixing, two necessary ingredients for the MSW explanation of the solar neutrino problem. Finally, and conclusively, in 2002 the Sudbury Neutrino Observatory measured the total neutrino flux from boron decay in all three flavors, and showed that this was about three times the flux in electron neutrinos, consistent with MSW oscillations. The Sudbury experiment also showed that the total flux was consistent with the predictions of Bahcall's standard solar model to within the uncertainties of about 10 percent.

The solution of the solar neutrino problem not only confirmed our understanding of the physics of energy generation in the Sun—and by extension in other stars—but also provided a dramatic illustration that astrophysical systems are likely to be one of the most important laboratories in which to pursue new physics in the next century, and thereby helped to inspire the growing interest of the physics community in phenomena such as dark matter, dark energy, and inflation. Ray Davis won the 2002 Nobel Prize in Physics with Masatoshi Koshiba, the leader of the Kamiokande experiment "for the detection of cosmic neutrinos." History is likely to judge that Bahcall should have shared in that prize.

Late in Bahcall's career a distinguished lecturer at Princeton remarked, "I've been visiting Princeton for over thirty years. Many things have changed: the buildings, the researchers, the important problems and puzzles in astrophysics, but one thing remains constant: John Bahcall is still working on the solar neutrino problem." Some in the audience thought this was a gentle tease, but many of us viewed the comment as a compliment: the solar neutrino problem resisted solution for almost 40 years, and without Bahcall's commitment, drive, scientific judgment, and standards of intellectual rigor it is likely that the massive experimental and theoretical efforts needed to solve this problem would have withered, and the solar neutrino problem would remain unsolved to this day.

ASTROPHYSICS RESEARCH

Bahcall's research in astrophysics spanned an extraordinary range. The areas of his major contributions include Galactic structure, supernovae, neutrino physics, stellar dynamics, black holes, dark matter, quasars, the intergalactic medium, solar physics, binary stars, galaxy clusters, X-ray astronomy, nuclear astrophysics, and statistical astronomy. Although mainly a theorist, he led successful observational campaigns with the Hubble Space Telescope and other telescopes. He had a connoisseur's appreciation for which observations were both important and believable, and a gourmet's contempt for those that were not. His signature accomplishments are discussed below.

The centers of most galaxies and perhaps some star clusters contain massive black holes. The phase-space distribution of stars close to these black holes should be in thermodynamic equilibrium due to gravitational encounters between the stars; however, the usual Maxwell-Boltzmann distribution cannot apply because it would lead to a divergent density close to the black hole. This problem was first investigated by Jim Peebles in 1972, who argued that the steady-state solution could be determined by requiring a spatially constant radial current of stars into the black hole, which in turn implies that the stellar number density should be a power law in radius, $n(r) \propto r^{-9/4}$. Bahcall and his postdoc Richard Wolf found, remarkably, that this simple and elegant argument was incorrect; the steady state is determined by requiring a constant current in energy, not number. They showed that the correct solution led to a different power law, $n(r) \propto r^{-7/4}$, and derived an exact numerical solution for the rate of consumption of stars by the black hole.[3] The Bahcall-Wolf model is now the standard of comparison for observational and theoretical studies of the stellar distribution in the centers of galaxies. One of the intriguing mysteries about the center of our own Galaxy is that it does not appear to follow the Bahcall-Wolf model, and the reasons for this discrepancy are not yet understood.

Bahcall spent the summer of 1972 in Israel, observing on the 102 cm telescope at the newly opened Wise Observatory with his wife, Neta. During that period, they took repeated photographic images of areas on the sky where X-ray point sources had been discovered by the Uhuru satellite, launched a couple of years earlier. Following a suggestion by W. Liller, they examined the stellar system HZ Her and showed that it varied in brightness with the same period and the same phase as the X-ray source Her X-1, thereby establishing that they were the same object, most likely a neutron star orbiting a main-sequence star and accreting material from it. This was one of the first low-mass X-ray binary stars to be identified and is probably the most studied of its class. The system exhibits three periodicities: a pulsation period of 1.24 seconds, an orbital period of 1.7 days, and a mysterious 35-day period that may be due to precession of an accretion disk around the X-ray source.

When participating in the design of the Hubble Space Telescope (HST), Bahcall and his young colleague Ray Soneira found that the density of bright stars in the sky was much smaller than the planners had been assuming. This was a serious problem because bright reference or “guide” stars are needed to point the telescope accurately. Their work led to a revision of the requirements document for the telescope and also sparked Bahcall’s interest in Galactic structure. The climax of his work in this subject was the development, with Soneira, of one of the most influential models for the distribution of mass and stars in the Milky Way Galaxy. The Bahcall-Soneira model was fit to a wide range of star counts and other data, precisely specified, and simple to reproduce, and was among the first models of the Galaxy to be informed by the assumption that the properties of our Galaxy should be similar to those of other galaxies. The paper describing the Bahcall-Soneira model has been cited almost a thousand times since its publication in 1980; remarkably, after three decades the citation rate shows no sign of decline.

Quasars were discovered by Maarten Schmidt at Caltech in 1962, and much of Bahcall's work in the 1960s was on the use of quasars to probe the properties of gas in the intervening intergalactic medium. A 1965 paper with Ed Salpeter at Cornell was the first to suggest that the intergalactic gas was clumpy and thus would produce a large number of sharp absorption lines in the quasar spectrum, a phenomenon that became known as the "Lyman-alpha forest" after its discovery. Bahcall and Salpeter originally thought that the clumps would most likely correspond to clusters of galaxies. It was only recognized in the 1990s that the "forest" was produced by a smoothly fluctuating intergalactic medium, and observations of the forest now provide an exquisitely sensitive test of cosmological models. Bahcall and Salpeter were also the first to use the properties of quasar spectra to constrain time variation of the fine-structure constant, a topic that remains active and controversial today and to which Bahcall continued to contribute. He provided the first quantitative methods for absorption-line analysis, replacing identification of lines by eye with a rigorous statistical analysis. Bahcall and Lyman Spitzer were also the first to recognize that many quasar absorption lines arise from extended gaseous halos around normal galaxies. Bahcall's early work on absorption lines motivated much of his initial interest in HST, and when the telescope was finally launched he led a key project to study these systems.

One of the central debates about quasars in the decades after their discovery was whether their redshifts were cosmological—due to the expansion of the Universe and therefore implying that the quasars were at immense distances—or arose from some other mechanism, perhaps gravitational redshift or ejection at relativistic velocities, which would imply that quasars were a thousand times closer. Throughout this controversy, Bahcall was one of the most eloquent advocates of the cosmological explanation. When I was a graduate student the primary reference on this subject was a brief book titled The Redshift Controversy that arose from a 1972 debate organized by the American Association for the Advancement of Science between Bahcall and Halton Arp, one of the main advocates for an unconventional interpretation of large redshifts. In the two decades since then, the evidence that quasar redshifts are cosmological grew steadily stronger, in part due to Bahcall's work. For many of us the most convincing and dramatic evidence came finally from a large sample of HST images of nearby quasars obtained by a team led by Bahcall. The images showed clearly that most, if not all, of the quasars were located at the centers of host galaxies and that the properties of these galaxies were consistent with the cosmological interpretation of the quasar redshift.

Large-area neutrino telescopes are designed to detect high-energy neutrinos from astrophysical sources such as active galactic nuclei and gamma-ray bursts. In these sources the escaping energy is likely to be distributed among cosmic rays (protons), electromagnetic radiation (gamma rays), and neutrinos in similar amounts. Starting with this argument, Bahcall and his young colleague Eli Waxman calculated an upper bound to the flux of high-energy neutrinos from the known flux of cosmic rays. The Waxman-Bahcall bound is now a benchmark flux for neutrino telescopes; the recently completed Ice Cube Neutrino Observatory at the South Pole is the first facility that will be able to test whether this benchmark is achieved in nature.

Most of Bahcall's calculations have stood the test of time remarkably well. One exception was his work on dynamical determinations of the total density of matter in the solar neighborhood, a problem first examined in 1922 by the Dutch astronomer Kapteyn. In a careful 1984 study Bahcall analyzed the spatial distribution and kinematics of nearby giant stars and concluded that about half of the total material in the disk near the Sun was in some unobserved or "dark" form (e.g., not visible stars, neutral or ionized gas, or dust). This was a controversial result, both because the vast majority of dark matter is expected to be found in the (spherical) halo of the Galaxy but not in the (flat) disk, and because later analyses using different types of stars found no evidence for dark matter in the disk. The controversy was eventually resolved when the Hipparcos spacecraft provided more accurate and complete distance and velocity information, and now measurements consistently show no significant evidence for dark matter in the solar neighborhood. Poorly understood systematic errors have plagued Galactic astronomy since the time of Kapteyn and continue to do so today—for example, plausible estimates of the speed of the Sun around the Galaxy still vary by 30 percent or several standard deviations—and the error in Bahcall's conclusions about dark matter in the disk is notable only because of his own very high standards.

SCIENCE POLICY

Perhaps Bahcall's most visible contribution to science policy was as the chair of the decade survey in astronomy and astrophysics, which was established by the National Research Council in 1989 to set priorities for astronomy and astrophysics for the 1990s. This was the fourth of six such surveys that have now been completed; these have proved to be extremely influential because, as Bahcall said at the time, "It is better for astronomers to make imperfect judgments about priorities for astronomy than it is to leave the decisions to Washington administrators." Bahcall's management of this difficult and often controversial process was characteristically efficient, but there were less obvious reasons for its success. He pushed through many tough decisions about the scope and management of the survey that were initially resisted by some of its stakeholders. He also spent enormous time and energy on consulting with the community—he solicited the opinions of hundreds of astronomers, wrote to the chair of every astronomy department in the United States, visited many funding agencies and congressional leaders and staffers, held open discussions at American Astronomical Society meetings, and appointed roughly 300 astronomers and physicists to 15 specialist panels that advised the main committee. The projects given high priority by the Bahcall committee, culled from a far larger list, included the Spitzer Space Telescope, an infrared telescope that was eventually launched in 2003; the Gemini telescopes, a pair of telescopes in Hawaii and Chile that now provide the primary access to large-aperture optical telescopes for most of the U.S. research community; and an accelerated program of small space astrophysics missions, chosen through peer review, which produced extraordinarily influential projects such as the Rossi X-ray Timing Explorer (RXTE), the Far Ultraviolet Spectral Explorer (FUSE), the

Wilkinson Microwave Anisotropy Probe (WMAP), the Galaxy Evolution Explorer (GALEX), and the Swift Gamma-Ray Burst Mission.

Bahcall also served as president of the American Astronomical Society from 1990 to 1992 and was president-elect of the American Physical Society at the time of his death. He participated in innumerable planning and review committees for solar neutrino experiments. In 2001 he chaired the National Underground Science Laboratory Committee, which focused attention on the Homestake mine as the best U.S. site for a national underground laboratory for particle physics, nuclear physics, astrophysics, biology, and geology. By now some $300 million has been committed from federal and state funding and private philanthropy toward the construction and science of the Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake.

THE HUBBLE SPACE TELESCOPE

Bahcall served as interdisciplinary scientist on the Space Telescope Science Working Group from 1973 to 1992 and became one of the most articulate and effective advocates for the telescope during its rocky path to launch in 1990 and successful operation a couple of years later. At that time political advocacy in Congress and the Executive Branch for public investments in advanced scientific facilities was far less common, and far less accepted, than it is today, and Bahcall and his colleagues had to learn as they lobbied.[4] In the words of Bob O'Dell, the project scientist, "No one had more conviction of the rightness and value of Space Telescope than John. Just no one involved anywhere in the project ... I was feeding him ammunition and he was just blasting, blasting away, charging off in the right directions, and just all on his own. No one delegated him. No one asked him." His efforts were so effective that at times he orchestrated both the questions and the answers in congressional subcommittees.

Bahcall's activism was only one component of his contributions to the Hubble Space Telescope. In addition to revising the requirements for guide star acquisition, he invented and implemented the Snapshot observing mode, in which the telescope observes objects from a pool of targets scattered around the sky to fill in otherwise wasted gaps in the telescope schedule. Twenty years later, HST takes over 500 snapshot observations per year.

In January 2004 the final servicing mission to HST was abruptly canceled in the wake of the loss of the shuttle Columbia. Bahcall's last contribution to HST was to lead a massive and successful advocacy effort to reinstate the servicing mission and thereby enhance HST's capabilities and extend its lifetime by at least five years. This was a controversial position at the time even among astronomers, many of whom felt that HST's most important discoveries were in the past, but Bahcall felt that a working, state-of-the-art telescope should not be abandoned for future missions that might be subject to delay, cancellation, or downsizing. It is probably too early (in 2011) to say whether Bahcall's view was correct. As he predicted, HST has gone on to make exciting new discoveries during a period of delays and cancellations in major new NASA missions. But some would argue that the ongoing expense of HST has itself been one of the causes of these difficulties.

THE INSTITUTE FOR ADVANCED STUDY

Bahcall arrived at the Institute for Advanced Study at Princeton in1968 and remained until his death almost 40 years later. During that time, he established a unique—though often imitated—model for postdoctoral training in astrophysics. The central ingredient of that model was a large, rotating group of postdocs who were aggressively recruited by Bahcall from the most promising young researchers worldwide and then given complete freedom to work on whatever subjects they chose. He spent an average of two hours a day in scientific discussion with them—at coffee and lunch and in one-on-one discussions as well. He collaborated with many of them but was happiest when they wrote good papers on their own or with one another. He celebrated their birthdays and the birth of their children, met with their parents (including mine), worried about their personal lives, and worked to find them good jobs with the intensity of a father seeking good marriages for his daughters. He would have made a remarkably successful rabbi if he had chosen that career path, but perhaps a more apt comparison is with Mario Puzo's fictional hero the Godfather, who shared John's commanding presence, wide-ranging network of personal connections, and intense loyalty. Well over 100 young researchers held postdoctoral fellowships at the institute during John's tenure, and a remarkable number later became leading theoretical astrophysicists. Consider, for example, the Warner Prize of the American Astronomical Society, awarded annually for contributions to observational or theoretical astronomy by a researcher 35 years old or younger—over the last 30 years, over a third of the Warner Prize winners have spent postdocs under Bahcall's mentorship at the institute.

Bahcall had a soft spot for talented young physicists who were interested in migrating to astrophysics, partly because he liked taking scientific risks and liked others who did so as well, and partly because he and Neta had followed the same path. (He said that when he arrived at the Institute for Advanced Study his first project was to read George Abell's introductory astronomy textbook from cover to cover so that he would know some astronomy.) A number of the physicists he hired are now leaders in the international astrophysics community; one of them, Avi Loeb, comments,

> John was the most influential matchmaker in my life. He introduced me to astrophysics with which I have had the longest love relationship in my life. I met my wife only later. She says that according to Jewish tradition, a matchmaker who arranges for three long-lasting relationships is privileged to have a place in heaven. There is no doubt in my mind that John has an honorable place in heaven.

For several decades Bahcall ran the famous "Tuesday lunch," now renamed "Bahcall lunch," at which local and visiting astronomers and physicists were asked to describe their current research and to report on new developments. Particularly in the years before the arXiv e-print service, Tuesday lunch was one of the most effective ways for astronomers in the Princeton community to learn about new and exciting developments and discoveries. Bahcall's rules were simple: no use of the blackboard, no visual aids except for a single sheet of paper, and anyone who attended could be asked to speak without warning. The audience often included half a dozen current or future members of the National Academy of Sciences, and the questioning, usually led by Bahcall, was always piercing and occasionally ruthless. Some speakers were exhilarated by the experience, some were terrified by it, but all remembered it.

PERSONAL LIFE

John Bahcall was born in 1934 in Shreveport, Louisiana. His path into physics was unconventional: his first interest was in athletics, and in high school he concentrated more on tennis than on academics, and in fact never took a science course. With a colleague, Max Nathan, he won the 1952 national high school debate tournament organized by the National Forensic League. He spent his freshman college year at Louisiana State University, where he studied mainly philosophy, then transferred to Berkeley. When required to take a science course to fulfill the graduation requirements, he picked a course in physics, which he later described as "the most difficult thing I had ever done." He switched majors and eventually was awarded an A.B. in physics in 1956. He then went on to graduate work in physics at the University of Chicago and Harvard, completing his Ph.D. in 1961. John had a clear set of priorities: family first, science second, and all other activities a distant third. He met his wife, Neta, at the Weizmann Institute in Israel, where she was a graduate student in physics. Like John, she eventually migrated to astrophysics and is now Eugene Higgins Professor of Astrophysics at Princeton University and a member of the National Academy of Sciences. Their three children all have followed research careers in science: Safi, Dan, and Orli received Ph.D.s in theoretical physics, cognitive psychology, and epidemiology, respectively. John was intensely interested in and proactive for his family; as just one example, he interviewed Orli's thesis adviser at Imperial College when she began working with him—and afterward had the grace to feel sheepish about having done so.

John's "other activities" included a lifelong interest in tennis and related sports; for some years he participated in the annual table tennis competition in the astrophysics department at Princeton University but was permanently banned after winning the championship for three years in a row. He later volunteered to play left-handed but this offer was not accepted. He loved to read, especially in Hebrew, which he taught himself as an adult and spoke whenever he could (although, I am told, with an accent that made his family wince). His awards and prizes included the National Medal of Science; Hans Bethe Prize of the American Physical Society; the Dan David Prize; Dannie Heineman Prize in Astrophysics; the Gold Medal of the Royal Astronomical

Society; the Russell Lectureship of the American Astronomical Society (the highest award of the two most prominent national astronomy societies); the Enrico Fermi Award of the Department of Energy (with Raymond Davis); NASA's Distinguished Public Service Medal and Exceptional Scientific Achievement Medal; the Comstock Prize in Physics of the National Academy of Sciences; and the Benjamin Franklin Medal in Physics (with Raymond Davis and Masatoshi Koshiba). He received honorary doctorates from the University of Pennsylvania, University of Chicago, University of Notre Dame, Hebrew University of Jerusalem, Ohio State University, and the University of Milan. John was elected to the National Academy of Sciences in 1976.

One illustration of his impact on astrophysics is the list of scholarships and fellowships established in his honor: the Bahcall fellowships for five-year postdoctoral research fellows at Institute for Advanced Study, the Bahcall Public Policy Fellowship of the American Astronomical Society, the Bahcall Physics Undergraduate Fellowship at Tel Aviv University, the Bahcall fellowships for postdoctoral researchers at the Ice Cube Research Center of the University of Wisconsin, the Davis-Bahcall Scholarships for Underground Science for students from South Dakota, and the Bahcall Award at the University of California in Santa Cruz to support research internships by undergraduates from Mexico.

CLOSING THOUGHTS

There is a well-known comment by Mark Kac about Richard Feynman, who was one of John's scientific heroes:

> There are two kinds of geniuses: the 'ordinary' and the 'magicians.' An ordinary genius is a fellow whom you and I would be just as good as, if we were only many times better. There is no mystery as to how his mind works.

Once we understand what they've done, we feel certain that we, too, could have done it. It is different with the magicians … Feynman is a magician of the highest caliber.

John was an "ordinary genius," and this is one reason why he was so influential with his younger colleagues. We all felt that if only we worked harder, or learned more physics, or had better judgment, or were bolder, we could make contributions as important as his.

A small number of scientific questions have dominated and steered scientific thought for millennia: what is the nature of matter, what is the origin of life, how big and how old is the Universe, and so forth. One of these questions is, how does the Sun shine? We now know the answer, due mostly to the efforts of a small number of giants of 20th-century physics. These include Hans Bethe, Willy Fowler, Ray Davis, and John Bahcall. John would have been immensely proud to be included in this group.

In May 2009 the final shuttle-servicing mission to the Hubble Space Telescope took place. The mission was a complete success, installing two new instruments, repairing two more, replacing batteries, gyroscopes, insulating panels, and command and guidance units. With this renovation, it is likely that the Hubble Telescope will produce spectacular science for a total of over 25 years, far longer than any other space astrophysics mission and longer than most ground-based science facilities. A very small part of the cargo in the shuttle for this mission were John and Neta's wedding rings, carried by astronaut John Grunsfeld as a tribute to John.

I AM INDEBTED TO professors N. Bahcall, A. Gould, A. Loeb, and W. Haxton for their insights.

NOTES

1. Much of the personal history in this memoir is taken from M. Hargittai and S. Hargittai, *Candid Science IV, Conversations with Famous Physicists* (London: Imperial College Press, 2004).
2. The standard reference on solar neutrinos is Bahcall's book, *Neutrino Astrophysics.* An authoritative account of Bahcall's role in the solution of the solar neutrino problem is in W. Haxton, "The scientific life of John Bahcall," *Annu. Rev. Nucl. Part. Sci.* 59(2009):1-20.
3. The Bahcall-Wolf solution had one significant flaw: it failed to account for stars that plunged directly into the black hole from nearly radial orbits in the "loss cone," an omission corrected a few months later by Juhan Frank and Martin Rees at Cambridge and Alan Lightman and Stu Shapiro at Cornell.
4. This story is told in Robert Smith, *The Space Telescope: A Study of NASA, Science, Technology, and Politics* (Cambridge, U.K.: Cambridge University Press, 1993).

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