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The Scientific Life of John Bahcall

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solar neutrinos, galaxies, quasars

Abstract

This article follows the scientific life of John Norris Bahcall, including his tenacious pursuit of the solar neutrino problem, his contributions to our understanding of galaxies, quasars, and their emissions, and his leadership of and advocacy for astronomy and astrophysics.

Contents

1. JOHN'S BEST DAY

John Bahcall once said that the best day of his scientific career may have been in 1964, when he received a call from Art Poskanzer, a nuclear chemist then working at Brookhaven National Laboratory. The call came at the urging of Ray Davis, who wanted John to know that Poskanzer's team—as well as the team of J.C. Hardy and R.I. Verrall from McGill University—had shown that the beta-decay lifetime of ^{37}Ca was indeed quite short. The ensuing conversation earned Art's group a bottle of champagne—carried by Willy Fowler to Brookhaven a few months later and opened in Director Maurice Goldhaber's office.

John Bahcall (**Figure 1**) was one of the dominant figures in twentieth century astrophysics and the intellectual leader of the 40-year effort to understand the physics behind the solar neutrino problem. Part of John's genius was his deep appreciation of the importance of teamwork in physics: He recognized that the goal of understanding the Sun required both experimentalists and theorists to chip away at many obstacles, some astrophysical, others nuclear and atomic. An accomplished tennis player (Louisiana state champion), John had learned early in life that one point could make a game, one game could determine a set, and one set could decide a match. John knew that the lifetime of ^{37}Ca was a crucial point in a very important doubles match. His doubles partner was Raymond Davis, Jr., and the match being played would decide the fate of a neutrino detector Ray hoped to construct deep within the Homestake Gold Mine in Lead, South Dakota (**Figure 2**).

John's roles in the Homestake effort and in the many solar neutrino endeavors that followed were those of both player and coach. His personal research drove the effort to accurately model the Sun, to understand its seismology and neutrino fluxes, and to exploit the neutrino flux as a test for new physics. But he also advocated for and helped focus many other activities that were important to the quest to solve the solar neutrino problem. This advocacy was crucial to the new generation of detectors that ultimately led to the discovery of neutrino oscillations.

John's interests and influence ranged far beyond solar physics. He authored nearly 500 technical papers, making major contributions to galactic modeling and structure, quasars, dark matter, the intergalactic medium, X-ray astrophysics, interacting binary stars, the astrophysics of black holes, and the production of ultrahigh-energy neutrinos. He wrote or edited nine books, including *Neutrino Astrophysics* (2) and *The Redshift Controversy* (3). He was one of the most recognized spokespeople for astronomy and astrophysics, frequently interacting with the media and publishing approximately 60 popular science articles. He led one of the world's premier astrophysics programs

Figure 1

John and Neta Bahcall, with their children, Safi, Dan, and Orli, in Israel for the presentation of the Dan David Award to John in 2003. This occasion was one of many in which John was honored by his colleagues. He also received the Warner Prize of the American Astronomical Society (1970); the NASA Distinguished Public Service Medal (1992); the Dannie Heineman Prize for Astrophysics (1994); the Hans Bethe Prize (1998); the National Medal of Science (1998); the Henry Norris Russell Lectureship of the American Astronomical Society (1999); the Benjamin Franklin Medal in Physics (2003); the Gold Medal of the Royal Astronomical Society (2003); the Fermi Award (2003); and the Comstock Prize of the National Academy of Sciences (2004). Photograph courtesy of the Institute for Advanced Study.

at the Institute for Advanced Study (IAS), Princeton. There he mentored generations of young postdocs and fellows—nearly 300 of the field's finest young researchers—recruiting them, following their progress in research with close attention, and helping many find good positions when the time came to leave the IAS. He presided over the Tuesday astronomy luncheons (now known as the Bahcall lunches), which provided a weekly opportunity to grill visitors and locals on their latest work. Together with Lyman Spitzer, Jr., he was a tireless advocate for the Hubble Space Telescope and the Space Telescope Science Institute. He chaired the ad hoc committee that jump-started the effort to create the Deep Underground Science and Engineering Laboratory (DUSEL).[1] He served as President of the American Astronomical Society, led the 1990 National Research Council's decadal survey for research and instrumentation in astronomy (the Bahcall Report), and served as President Elect of the American Physical Society.

2. SOLAR NEUTRINOS

2.1. The Early Days

In 1958, Holmgren & Johnston (4, 5) found that the cross section for $^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ was approximately 1000 times larger than expected, implying that the solar *pp* chain for synthesizing

[1]The Homestake Mine was recently designated as the future site of DUSEL.

Figure 2

Ray Davis and John Bahcall at the Homestake Mine, circa the late 1960s. Photograph courtesy of the Institute for Advanced Study.

^{4}He would have additional terminations beyond the ppI end reaction ^{3}He + ^{3}He → ^{4}He + 2p (see **Figure 3**). Higher-energy neutrinos from the new cycles fed by ^{3}He + ^{4}He, the ppII and ppIII cycles of **Figure 3**, could be measured by the techniques Davis had developed at Brookhaven (6). This was discussed by A.G.W. Cameron (7) and by Willy Fowler (8). Fowler noted that quantitative predictions required more information on reactions involving ^{7}Be, namely the rates for p + ^{7}Be, then unmeasured, and for e^- + ^{7}Be.

At the time, John Bahcall was a graduate student at Harvard, having finished his undergraduate studies at the University of California, Berkeley, in 1956 and his masters degree at the University of Chicago in 1957. In 1961, John began a postdoctoral appointment—a year with Emil Konopinski at Indiana University, working on weak interactions in nuclei. There John wrote a paper describing the temperature and density dependence of beta decay in stellar interiors. Willy Fowler, who refereed the paper for *Physical Review*, described the results to Davis, who then wrote to Bahcall in February 1962 to inquire about the rate for electron capture on ^{7}Be in the Sun. Bahcall and Davis note, in their entertaining "An Account of the Development of the Solar Neutrino Problem," that this question was the first of many they were to ask of each other in the decades to come (1). Bahcall's paper on bound-state and continuum electron capture on ^{7}Be appeared in *Physical Review* later that year (9).

Davis's inquiry reflected his interest in measuring neutrinos using the reaction ^{37}Cl (ν_e, e) ^{37}Ar, a detection scheme first suggested by Pontecorvo (10) and later discussed in some detail by Alvarez (11). In 1955, Davis completed an exploratory experiment at Brookhaven—the target was 1000 gallons of C_2Cl_4 buried 19 ft underground—that set an upper limit on the rate of solar neutrino captures of ∼40,000 solar neutrino units (SNU, a term John coined, where 1 SNU = 10^{-36} captures per target atom per second). If the pp chain were to operate entirely through the ppIII

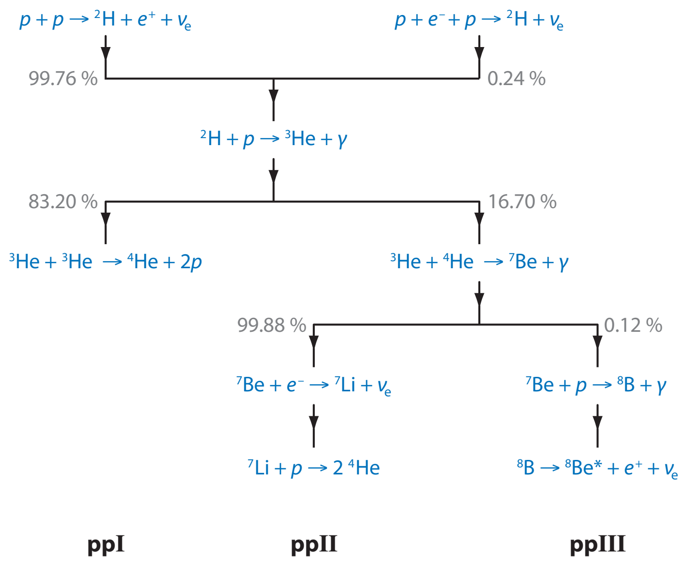

Figure 3

The *pp* chain. Each of the three cycles, ppI, ppII, and ppIII, is associated with a characteristic neutrino source. The competition between the cycles depends sensitively on the solar core temperature.

cycle, Davis estimated that the rate would be approximately 7.7 captures per day, or 3900 SNU, easily within reach in an improved experiment. Thus, it became important to understand the solar fate of ^{7}Be, which depends both on nuclear physics and on the Sun's central temperature.

The critical missing reaction rate, ^{7}Be(p, γ)^{8}B, was measured by Ralph Kavanagh in 1960 and found to be low (12). It became clear that the ppIII cycle was not dominant and that the measurement of the associated flux would be a daunting task. Precisely how daunting depended in part on the core temperature of the Sun.

In summer 1962, John became a research fellow in Willy Fowler's group at Caltech's Kellogg Laboratory, joining fellows Icko Iben, Jr. and Dick Sears. This group undertook the task of incorporating the new information on the *pp* chain into a model of the Sun in order to estimate the flux of solar neutrinos for the first time. As described by John (1), Sears performed the calculations using an energy-generation subroutine and opacity code originally developed by Iben, with the former adjusted by Bahcall and Fowler to reflect several new results on cross sections as well as John's formulation of electron capture. The model results were then used by John in a hand calculation of the neutrino flux. The model predicted an average temperature for the central core of 1.5×10^7 K and fluxes for ^{8}B and 861-keV ^{7}Be neutrinos of 3.6×10^7 and 1.0×10^{10} cm^{-2} s^{-1}, respectively. The paper noted the extreme sensitivity of the ^{8}B flux to temperature (13).

These fluxes, which later proved somewhat optimistic, were not encouraging. Although Davis was contemplating a very large experiment, 100,000 gallons of C_2Cl_4 housed in a cavity deep underground, the expected counting rate was approximately one event per day. The estimate was based on a cross section for neutrino capture on ^{37}Cl derived from the known electron-capture rate of ^{37}Ar. This rate, the only experimental information available, corresponded to a transition between the ground states of the parent and daughter nuclei.

During a seminar presented by John at the Niels Bohr Institute in summer 1963, Ben Mottelson raised a question about the possible role of excited states in ^{37}Ar. John addressed this question by performing a calculation in which the states of ^{37}Ar and ^{37}Cl—as well as those in the analog nuclei ^{37}K and ^{37}Ca—were modeled as $1d^3_{3/2}$ hole configurations in a ^{40}Ca core, a treatment that generates in ^{37}Ar a $T = 3/2$ excited state, the isospin analog of the ^{37}Cl ground state, and thus a superallowed transition to this state (14). Consequently, John found a total cross section for ^{8}B neutrinos nearly 18 times that of the ground-state cross section: The ^{37}Cl experiment would be primarily sensitive to neutrinos from the highly temperature-dependent ppIII cycle. Most important, apart from small corrections due to charge-symmetry violation, the same physics would govern the analog beta decay $^{37}\text{Ca} \rightarrow {}^{37}\text{K}$, greatly shortening the half-life to a predicted 0.13 s. Although ^{37}Ca had not yet been observed, it was apparent that there was an experimental method for confirming the calculation, demonstrating the potential for the chlorine detector to measure ^{8}B neutrinos. John estimated that his calculation would be reliable to $\pm 25\%$.

In March 1964, Bahcall (15) and Davis (16) published companion articles in *Physical Review Letters* arguing that the envisioned 100,000-gallon experiment, if conducted deep underground, would succeed in measuring solar neutrinos and thus in determining the temperature of the solar core. Bahcall discussed uncertainties in detector cross sections and solar model flux predictions, concluding that the expected counting rate would be (40 $\pm$ 20) SNU. Davis reported the results of a 1000-gallon pilot experiment that had been conducted at a depth of 1800 meters water equivalent (m.w.e.) in an Ohio limestone mine and argued that a 100,000-gallon experiment conducted at 4000 m.w.e. would record between 4 and 11 solar neutrino events per day, with backgrounds a factor of 10 or more below this level.

John learned from Poskanzer's call in 1964 that ^{37}Ca had been discovered. Its measured half-life, 0.17 s, was short and within the 25% uncertainty John had estimated for his calculation (17, 18). John recognized immediately that this confirmation of one of the key assumptions in the Bahcall and Davis companion papers placed the chlorine experiment on firm ground. It would be possible to probe the Sun's core with solar neutrinos.

2.2. The Standard Solar Model

In a follow-up paper to the Bahcall, Fowler, Iben, and Sears neutrino flux calculation, Sears explored the sensitivity of the predictions—notably $\phi(^8\text{B})$—to input assumptions, such as the solar composition (19). Sears postulated a homogeneous zero-age-main-sequence Sun (because the proto-Sun likely passed through a fully convective Hayashi phase), then fixed the initial heavy-element abundance Z to the observed (but then poorly determined) surface abundances. He adjusted the He/H ratio, Y/X, to reproduce the Sun's luminosity after 4500 Ma. He found that Z and Y were correlated, with the lowest Z explored (0.020) yielding the lowest primordial helium abundance (Y $=$ 0.272) and the lowest $\phi(^8\text{B})$, 1.9×10^7 cm^{-2} s^{-1}. The standard solar model (SSM) neutrino flux sensitivity to input parameters would concern John and his colleagues for four decades.

In April 1968, Davis, Harmer & Hoffman (20) announced an upper bound on the solar neutrino-capture rate of $\lesssim$3 SNU, so that $\phi(^8\text{B}) \lesssim 0.2 \times 10^7$ cm^{-2} s^{-1}, based on the initial two runs of the Cl detector. The baseline for comparison to theory came from the SSM calculation of Bahcall & Shaviv (21), which was scheduled for publication in *Astrophysical Journal*, having gone through final revisions in January 1968. This paper reflected important progress in the nuclear physics of the *pp* chain, including Parker's remeasurement (22) of the critical $^7\text{Be}(p, \gamma)^8\text{B}$ reaction and new measurements that substantially increased the cross section for $^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$ (23, 24; A.D. Bacher & T.A. Tombrello, unpublished manuscript). It also identified the heavy-element abundance and the rate for $p + p \rightarrow d + \nu_e + e^+$ as key uncertainties affecting the ^{8}B flux prediction, $\phi(^8\text{B}) \sim 1.3(1 \pm 0.6) \times 10^7$ cm^{-2} s^{-1}.

The comparison with experiment also depended on the cross section for neutrino absorption on ^{37}Cl, which by this time was firmly established. A suggestion by Charlie Barnes had led to a more precise relationship between ^{37}Ca beta decay and neutrino capture on ^{37}Cl: In 1964, Bahcall & Barnes (25) pointed out that the model-dependent Gamow–Teller distribution for neutrino capture could be extracted from the delayed proton spectrum following ^{37}Ca(β^+) ^{37}K. By 1966, the first measurement of the delayed protons had been made (26).

Davis, Harmer & Hoffman observed that their upper bound was approximately a factor of seven below the SSM prediction. Their paper was accompanied by one from Bahcall, Bahcall & Shaviv (27), updating the Bahcall & Shaviv results to reflect a new determination of Z and the neutron lifetime (and thus the weak axial coupling g_A). These changes lowered the counting rate of their most probable model to 7.7 $\pm$ 3.0 SNU, a range still outside the experimental limit.

The experiment had given an unexpected answer, and the wait for independent confirmation would be a long one. The result obtained by Davis, a limit of a fraction of a count per day in a massive volume of organic liquid, seemed incredible to many. Transcripts of discussions that occurred during a 1972 conference on solar neutrinos in San Clemente (R. Davis, Jr., unpublished material) show Davis responding patiently to various skeptics, describing tracer and other cross-checks he had performed to verify the efficiency of the nearly single-atom counting.

Similarly, on the theoretical side, a few years of effort on *pp*-chain nuclear physics and metallicities had reduced the SSM prediction from 40 to ~8 SNU: Was a remaining factor-of-three discrepancy a serious matter? As the necessary adjustment in the SSM was a reduction in the Sun's core temperature by ~5%, "no" was perhaps not an unreasonable answer. One early suggestion was the so-called low Z model developed by Iben (28) in which the convective zone's metals were attributed to the accumulation of dust and other debris during main-sequence evolution, whereas the core's much lower Z reflected the true composition of the primordial gas cloud. Indeed, Bahcall, Bahcall & Shaviv (27) had concluded "if the usual theory of stellar interiors is correct, then the heavy element abundance Z must be less than 2% by mass in order for the predicted neutrino-capture rate not to exceed the observed value." Another suggestion was the mixed Sun model proposed by Ezer & Cameron (29), which kept the Sun's central opacity low by replenishing the core's hydrogen. Over the next 20 years, many nonstandard solar models were proposed, with most designed to solve the solar neutrino problem by producing a cooler Sun.

John's views about the SSM and the solar neutrino puzzle slowly evolved. In his 1989 book *Neutrino Astrophysics*—published some 27 years after his initial work on this problem—he offered an explanation for the solar neutrino problem:

> Simplicity. Our models of the solar interior and of neutrino propagation are not strongly constrained by experimental data. My guess is that a decade of new experiments will show that we need more sophisticated theoretical models, astrophysical and physical (2, p. 33).

But John would remark, just a few years later, that perhaps the inclusion in his book of a chapter on nonstandard solar models had been a mistake, a throwback to earlier times. What changed his views?

John's exploration of possible uncertainties in the SSM began in earnest with the 1969 paper he coauthored with Neta Bahcall and Roger Ulrich (30). There was a great deal to explore: By one count, the modern SSM has 19 adjustable parameters, for instance, quantities such as the solar age and luminosity, individual metal abundances, nuclear cross sections, and the coefficient for diffusion. John's collaboration with Roger Ulrich extended over eight papers and included studies of the consequences of changes in composition, magnetic fields, and radiative opacity (a collaboration with the Los Alamos opacity group) on SSM predictions. It included detector absorption cross sections, as new ideas emerged for follow-ups to the chlorine experiment, and John's first paper on helioseismology (which, interestingly, made the point that p-mode frequencies were then not a restrictive constraint on neutrino fluxes).

John's collaboration with Neta, of course, transcended their 30 joint papers, encompassing a lifetime of shared experiences and three children, Safi, Dan, and Orli, who gave John much joy. John, describing the beginning of this lifelong collaboration (31), told of meeting a graduate student on a trip to Israel in 1965 "with a beautiful smile that stole my heart."

At the 1984 Homestake Solar Neutrino conference, John expressed the view that no good solution existed:

> The standard solar model predicts—if nothing else happens to the neutrinos on the way to the Earth—about 6 SNU, with an effective 3σ uncertainty of about 2 SNU. This is in conflict with observations reported by Keith Rowley at this conference, which yield about 2 SNU (with a small 1σ uncertainty of about 0.3 SNU). There is no accepted solution for this problem, although many have been proposed. . . . The discrepancy between theory and observation has remained approximately constant over the past 16 years, although there have been hundreds of careful and important papers refining the input data, the calculations, and the observations (32, p. 60).

Roger Ulrich once noted (33) the tendency "for workers in each of the three areas related to the [solar neutrino] problem—stellar interior theorists, particle physicists, and experimental physicists—to hope and occasionally believe that the solution lay in the other fellow's camp." However, John's comment above shows a broader skepticism about solutions, including those from particle physics. In 1980 (34), he expressed doubt about neutrino mixing scenarios because of the requirement of nearly maximal mixing: ". . .[I]t is difficult to resolve the difference between predictions based on the solar models and observations solely by invoking neutrino oscillations, if there are only three kinds of neutrinos coupled to each other."

Thus, John's Homestake talk focused on the need for more measurements: He presented his well-crafted argument that the proposed gallium experiment was needed to separate the innocent from the guilty. Because this experiment would be primarily sensitive to *pp* neutrinos, a minimum astronomical counting rate of 78 SNU was guaranteed for any standard or nonstandard solar model (assuming a steady-state Sun). In contrast, neutrino oscillations would yield a counting rate of about 38 SNU because complete mixing of three neutrino flavors was needed to account for the Cl results.

The radiochemical gallium experiment, proposed by the Russian theorist V.A. Kuzmin (35), was similar conceptually to the chlorine experiment but involved more complicated chemistry. Two extraction procedures had been designed, one for a $GaCl_3$-HCl solution and one for metallic liquid gallium. Davis played a central role in both efforts. A pilot experiment with 4.6 tons of $GaCl_3$ solution had been conducted at Brookhaven. Although Bahcall passionately advocated for a full-scale experiment, and although two high-level review committees (headed respectively by G.T. Seaborg and R. Vandenbosch) recommended proceeding, a U.S. experiment was never mounted. The cost of gallium procurement was the primary obstacle. Brookhaven's collaborators, after nearly eight years, moved ahead on GALLEX as a primarily European effort, led by Till Kirsten and colleagues (36). The group quickly obtained commitments from three national science ministries. Similarly, the 60-ton Soviet-American Gallium Experiment (SAGE) was mounted at the Baksan Laboratory, under the direction of Vladimir Gavrin, George Zatsepin, and Tom Bowles (37). SAGE and GALLEX began operations in January 1990 and May 1991, respectively.

While the gallium saga played out, efforts were under way to reduce backgrounds in the Kamiokande proton decay detector so that it could operate at a threshold below the ^8B neutrino end point. The experimenters reached thresholds of 9 MeV and later 7.5 MeV. Data from the first 450 days of running were reported in the July, 1989 *Physical Review Letters* (38)—a rate 46% of that expected for SSM fluxes: Confirmation of the Homestake results had taken two decades. Kamiokande II/III operated from December 1985 until July 1993, accumulating 2079 live detector days of data (39).

2.3. Neutrino Oscillations

These experiments influenced John's views on the solar neutrino puzzle, but so did new developments in theory. In 1986, Mikheyev & Smirnov (40, 41) evaluated the effects of matter on solar neutrino oscillation probabilities, using a result for the effective neutrino mass originally derived by Wolfenstein (42, 43). The result, nearly complete flavor oscillation of $\nu_e \rightarrow \nu_\mu$ even for quite small mixing angles θ_{12}, is known as the MSW effect. The effect was quickly recognized to be a consequence of adiabatic level crossing (44–46). Within the Sun, charge-current scattering of a ν_e off electrons generates a density-dependent contribution to the neutrino effective mass. Consequently, solar neutrinos can encounter a critical density on their way out of the Sun, where this effective mass just cancels the vacuum mass difference between two neutrino mass eigenstates. The crossing of this critical density can generate a nearly complete change in flavor and thus low counting rates in detectors sensitive only to Cl, Ga, or primarily to (Kamiokande II/III) electron neutrinos. Thus, the solar neutrino problem might have an elegant particle physics solution.

John joined Ray Davis, Jr. and Lincoln Wolfenstein in writing the 1988 *Nature* review "Solar Neutrinos: A Field in Transition," which summarized a solar neutrino conference that the Institute for Theoretical Physics, Santa Barbara, had hosted the previous year (47). The paper discussed the MSW mechanism as well as very early results from Kamiokande II (which had already established an upper bound on the ^{8}B neutrino flux in conflict with the SSM). The paper did not indicate which type of solution—solar or particle physics—the authors preferred. Instead, it stressed that the field was undergoing a transition, driven by new experiments. In 1989, anticipating results from SAGE and GALLEX, John and I explored MSW solutions to the solar neutrino problem as a function of possible gallium outcomes, finding that for a wide range of counting rates, 20–100 SNU, distinct "islands" of solutions appeared in the $\delta m^2 - \sin^2 2\theta$ plane—adiabatic, nonadiabatic, and large-mixing-angle solutions (48).

The following year (1990), John and Hans Bethe decided to place their bets: In a *Physical Review Letters* article that was widely read, they argued that the solution to the solar neutrino problem was the MSW mechanism, and chose from among possible MSW solutions nonadiabatic conversion with a small mixing angle (49). Their first conclusion was correct, but the second step proved premature, as it would take the field another decade to sort out the competing solutions. Although they were aware that large-mixing-angle solutions would be allowed for gallium outcomes above 20 SNU, John and Hans argued that neutrino mixing angles would likely be small, similar to those known from the quark mass matrix, thus disfavoring this solution. They also argued against a hybrid small-angle solution—one where the high-energy portion of the ^{8}B flux experiences an adiabatic crossing, suppressing these neutrinos, while the lowest-energy neutrinos reside in the nonadiabatic portion of the MSW triangle, and thus survive to be counted in SAGE and GALLEX—because the Kamiokande II rate for high-energy neutrino events was nearly half the SSM prediction. John and Hans pointed out that one consequence of their selected solution could be a very low gallium counting rate, perhaps as low as 5 SNU.

But the gallium experiments produced a different result. The first runs from SAGE (50) yielded a counting rate of 20^{+15}_{-20}(stat.) $\pm$ 32(syst.) and a 90% C.L. upper bound of 79 SNU. This result was compatible with all three oscillation solutions. The first result from GALLEX (51) was a counting rate of 83 ± 19 ± 8 SNU (1σ), leading the collaboration to note that "astrophysical reasons remain as a possible explanation of the solar neutrino problem." Indeed, the final SAGE and GALLEX results were to converge to values quite close to John's minimum astronomical rate, 78 SNU.

In 1993, with the gallium results in hand, John and Hans asked the question (52) "Do Solar Neutrino Experiments Imply New Physics?" They answered that the general pattern of fluxes derived from the Cl, Kamiokande II, and GALLEX/SAGE experiments "suggest[s] that new physics is required beyond the standard model" but cautioned that all of their arguments "depend to some extent on our understanding of the solar interior." They relied on extensive Monte Carlo studies of SSM uncertainties in reaching these conclusions. John began a new series of SSM investigations, anchored by his collaboration with Marc Pinsonneault, but also including David Guenther, Sarbani Basu, Jørgen Christensen-Dalsgaard, Aldo Serenelli, and others. The work included the effects of helium and heavy-element diffusion on the SSM: Such corrections became important as the quality of the data from helioseismology improved. This allowed the modelers to test SSM predictions against precisely known data, including the depth of the convective zone and the Sun's interior sound speed. The SSM sound speed was found to agree with helioseismology to better than 0.2% throughout almost the entire Sun. John argued in several contexts that this was perhaps a more severe test of the SSM than solar neutrino spectroscopy.[2] He was enormously excited about this SSM success, concluding that it was now very likely that the solution to the solar neutrino problem would be new physics.

Further evidence that the SSM might not be at fault came from the neutrino flux systematics revealed by the experiments. Although many solar model "dials" can be turned, in the end the predicted neutrino fluxes are strongly correlated with one solar property—the core temperature. If one lowers the temperature by a few percent, then (*a*) $\phi(pp)$ is nearly unchanged (provided that the model is constrained to reproduce the luminosity), (*b*) $\phi(^7\mathrm{Be})$ is somewhat suppressed, and (*c*) $\phi(^8\mathrm{B})$ is significantly suppressed. But the results from Kamiokande II/III and GALLEX/SAGE seemed to require the ^{7}Be neutrino flux to be the most sharply suppressed. A nice illustration of the conflict between the measured fluxes and trends based on the solar core temperature is given in **Figure 4**.

On June 5, 1998, the Super-Kamiokande collaboration announced evidence for neutrino mass (55), attributing an anomaly seen in atmospheric neutrino data to oscillations. Although this discovery was not directly related to solar physics—the results were consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillations and corresponded to a δm^2_{23} too large to generate an MSW crossing in the Sun—it was clearly a game changer. The neutrino sector included the basic ingredients, massive neutrinos and flavor mixing, needed for a particle physics solution of the solar neutrino problem.

On June 30, 2001, the Sudbury Neutrino Observatory (SNO) collaboration submitted a paper on its initial charged-current (CC) and elastic scattering (ES) results to *Physical Review Letters* (56): Assuming no flavor mixing, the two rates were found to be inconsistent at 3.3 σ. A second paper, submitted on April 19, 2002, provided dramatic evidence for oscillations: The solar neutrino flux was measured independent of flavor through the neutral-current (NC) breakup of deuterium (57). The three channels, CC, ES, and NC, agreed and pointed to a solution in which two-thirds of the ^{8}B neutrinos arrive at Earth as heavy-flavor neutrinos. The SNO collaboration deduced a total flux, $[5.09^{+0.44}_{-0.43}(\mathrm{stat.})^{+0.45}_{-0.43}(\mathrm{syst.})] \times 10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, consistent with the SSM prediction. Ironically, the mixing angle $\theta_{12} \sim 35°$ is large—nature chose not to enhance the effects of a small mixing angle through the MSW mechanism.

[2] Curiously, recent reanalyses of photospheric absorption lines have altered solar abundance estimates, causing significant deterioration in the agreement between SSM predictions and sound speeds derived from helioseismology (53).

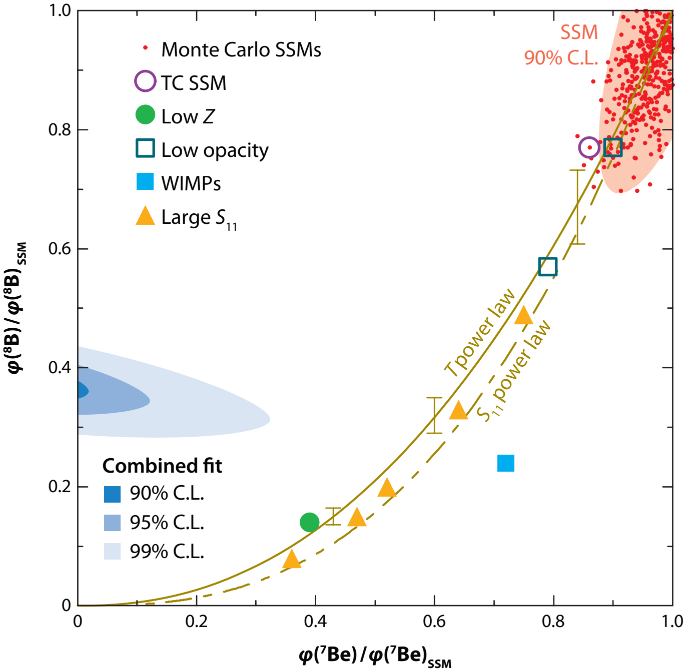

Figure 4

Illustration of the inconsistency between measured neutrino fluxes and the general trends in standard and nonstandard solar models—a pattern of neutrino fluxes reflecting the solar core temperature. Abbreviations: TC SSM, Turck–Chièze standard solar model; WIMP, weakly interacting massive particle. Reproduced from Reference 54 with permission.

Forty years earlier, Bahcall, Iben, and Sears had taken on a formidable task, construction of a model of the Sun that could quantitatively predict neutrino fluxes. John stayed with this task, recognizing its significance. The model's input parameters were refined through many years of patient measurement by nuclear and atomic experimentalists: John's advocacy helped keep these communities motivated. Improvements in the quantum mechanics governing opacities were needed, and new effects such as diffusion had to be incorporated into the model in response to the new data from helioseismology. When the model converged, John assessed its precision in careful studies and became convinced of its accuracy. Finally, when the SNO collaboration finished its work, he had the pleasure of an answer, one that rewarded his hard work and demonstrated its lasting importance.

In a television interview (58), John was asked about how he reacted to the results from SNO. He responded, "I was called right after the [SNO] announcement was made by someone from the *New York Times* and asked how I felt. Without thinking I said, 'I feel like dancing, I'm so happy.' . . .It was like a person who had been sentenced for some heinous crime, and then a DNA test is made and it's found that he isn't guilty. That's exactly the way I felt."

3. BEYOND THE SUN

The solar neutrino problem was John's lifelong scientific passion, but it certainly did not define the boundaries of his interests. John made lasting contributions to a wide range of problems at the forefront of physics and astrophysics, including low-energy weak interactions, quasar absorption line analyses, galactic modeling, dark matter, neutron star structure and cooling, the stellar environments around massive black holes, and high-energy cosmic neutrinos. Indeed, such problems constitute the majority of his scientific work.

3.1. Beta Decay and Electron Capture

John once noted that Emil Konopinski's *Theory of Beta Radioactivity* was perhaps the book that had influenced him the most. In 1961, as a postdoc working in Emil's group, John sat in on a course based on the notes that became this book, making up his own practice problems, and solving and publishing them. His understanding of weak interactions in atoms and nuclei provided the foundation for his life's work.

John's involvement with the solar neutrino problem began with his paper on beta decay in stellar interiors. Many of his other studies focused on laboratory phenomena, including bound-state beta decay, relativistic effects in atoms, electron-capture rates from higher atomic states, and exchange and overlap effects in beta decay. The last topic deserves special note, as John's paper (59) contains several results that have survived the test of time.

Twenty-five years after this paper was published, the possible discovery of a 17-keV neutrino caused some excitement. The initial experiment revealed an anomaly in the electron spectrum from tritium beta decay, which, because of the 18.6-keV energy release, appeared within 2 keV of the end point. Thus, the outgoing electron is very slow: This is a limit where exchange corrections—the decay electron goes into a bound atomic state while the spectator atomic electron is shaken off—become large. I used John's 1963 exchange corrections to estimate the effects, which accounted for part of the observed anomaly. On seeing the paper, John called me to express his pleasure that his ancient paper had not been forgotten.

Tests of quark unitarity depend on determinations of V_{ud} from $0^+ \rightarrow 0^+\beta$ decay. These experiments require extraordinary precision, including very accurate determinations of the mass difference between the parent and daughter atoms. For example, Penning trap experiments have determined some mass differences to 50–100 eV. But the masses measured are those of the stable atoms. High-energy-release beta decays are essentially instantaneous, so that the daughter nucleus inherits the atomic configuration of the parent state. The energy loss in the subsequent atomic arrangement, a correction that should be applied to the Penning trap results, can exceed 100 eV in heavy atoms. This correction has recently been made in Fermi beta decay analyses (J.C. Hardy, private communication) using John's formula.

3.2. Quasi-Stellar Object Absorption Lines

In 1963, Maarten Schmidt (60) and Greenstein & Matthews (61) demonstrated that quasi-stellar radio sources (quasars) reside at great distances when they found that the redshifts of 3C273 and 3C48 were 0.158 and 0.3675, respectively. Quasar emissions include a continuum that extends into far-ultraviolet (UV) and X-ray frequencies. Quasars, or more generally, quasi-stellar objects (QSOs), were the focus of much of John's work in the late 1960s and then again three decades later, when the Hubble Space Telescope (HST) opened up new opportunities.

By 1967, QSOs were at the forefront of astronomy, recognized, because of Schmidt's work, to be significantly more common in the early universe than now. (The QSO distribution peaks at redshifts of two to three.) As powerful, early sources, they were potentially an important probe of cosmology and cosmological evolution. In particular, the discovery of the first quasar with redshift greater than two, 3C9, opened up some spectacular possibilities (62). Gunn & Peterson (63) showed that, for such a distant source, an absorption trough could appear in the continuous spectrum if there was sufficient neutral hydrogen in the intergalactic medium. This feature would be apparent in spectra measured from the Earth's surface, if redshifted into optical wavelengths. The trough is formed through absorption at the wavelength of Lyman-α photons as the light travels over cosmological distances.

Very soon after Gunn and Peterson's paper was published, Bahcall and Ed Salpeter wrote an article for *Astrophysical Letters* titled "On the Interaction of Radiation from Distant Sources with the Intervening Medium," in which they envisioned a scenario where the intervening gas was clumpy (64). In this scenario, the trough is replaced by a series of sharp absorption lines, displaced from the Lyman-α wavelength by the redshifts of the gas clumps. That is, the intergalactic medium can be probed at a variety of distances by the pattern imprinted on the spectrum of a distant QSO. The following year, the authors published a second article describing how, under favorable conditions, the wavelength, depth, and width of the absorption lines could constrain the temperature, chemical composition, and velocity dispersion of cluster gas (65). This paper noted that Bahcall, Peterson, and Schmidt had begun an examination of Schmidt's QSO spectra for this purpose. A few months later, the group described hydrogen and carbon absorption lines found in the spectra for a quasar at redshift 2.118, corresponding to absorption at redshift 1.949 (66).

In 1969, John teamed with Lyman Spitzer on the paper "Absorption Lines Produced by Galactic Halos," proposing, for the first time, that many of the QSO absorption lines with multiple redshifts are caused by gas in large extended halos around normal galaxies (67). This suggestion came long before the existence of such halos had been established by other observational means.

John worked intensively on the QSO absorption line problem for five years, producing approximately 30 publications. The early data were not of high quality, and there were questions about distinguishing absorption that might be associated with the QSO's immediate environment from that connected with intervening gas clouds. John attacked this problem by carefully examining the data and by numerical modeling, assessing in Monte Carlo studies the significance of multiple redshift systems, each of which might be characterized by multiply detected absorption lines. His was the first quantitative approach to absorption line analysis—replacing previous "by eye" identifications with an algorithm-based analysis that accounted for line strengths, expected line ratios, and other systematics. The times were exciting, as QSOs were new and appeared to open a door to the very distant universe. Part of that excitement was captured in a famous debate between John and Chip Arp on whether quasar redshifts were cosmological (3)—a debate John clearly won.

John's studies included correlations in QSO directions with those of galaxy clusters, bounds on the masses of QSOs, and the question of whether the fine structure constant might vary with cosmic time—a topic of significant interest today. (The possibility that α might not be constant had been suggested by Gamow as a factor that could complicate conclusions drawn from redshifts about the viability of a steady-state cosmological model.) This issue was re-examined in follow-up papers (68, 69) about the constancy of several metal line splittings for QSOs and radio galaxies, ultimately yielding $\alpha(-2000\ \mathrm{Ma})/\alpha(\mathrm{today}) = 1.001 \pm 0.002$. John's last paper on this subject was published in 2004 (70).

John's later advocacy for the HST reflected in part his early interests in QSOs: High-quality spectra could be obtained in the UV above the atmosphere, with very low background, thereby extending both the range of distances that could be probed and the number of lines that might be correlated for a given source. In particular, the HST was crucial in probing QSOs in the low-redshift universe. When the HST was carried into space in 1990, John returned to absorption line astronomy with a passion, as principal investigator of the HST Quasar Absorption Line Survey. The Survey collaborators studied some 80 lines of sight, effectively probing matter along each direction through redshift, making use of the Faint Object Spectrograph. The catalogs of

Lyman-α and metal absorption lines provide a detailed map of structure from the very nearby universe out to $z \gtrsim 3$. John was able to return to many of the themes he had explored in the late 1960s—such as the correlations of absorbers with galaxies—but with much finer data and within the context of contemporary efforts to model the formation and evolution of structure.

John's work spanned four decades and deeply influenced our understanding of QSOs and cosmological structure. He was involved in the key questions—the identification of QSOs with cosmological distances, their correlation with galaxies and clusters of galaxies, the utility of QSO light in absorption as a probe of the distribution of neutral hydrogen and metals, QSO number density evolution with redshift, QSO masses, and the role of QSOs as the central engines of host galaxies.

3.3. The Bahcall–Soneira Model of the Galaxy

In 1980, John Bahcall and Ray Soneira (71, 72) constructed a phenomenological model of the Milky Way based on the idea that models of our own Galaxy could be informed by observations of external galaxies, if we assume that the Milky Way is similar to other galaxies. The model's parameters were adjusted to reproduce star counts made in various directions in the sky, which then would provide a basis for extrapolating those counts (e.g., to fainter populations). This model was extensively developed by Bahcall and Soneira in the early 1980s, and it has remained in broad use ever since. It was motivated in part by the anticipated HST program to probe the universe at unexplored faint magnitudes. A reliable model of the galactic environment could help this program in many ways, such as in assessing, from stellar trends in the Milky Way, how unknown local stellar populations might interfere with cosmological surveys.

The model combined a thin exponential disk with a spheroid, or bulge, associating with each a distinct stellar population. The spheroidal component was assumed to be dominated by Population II stars (which are typically older, less luminous, cooler, and relatively metal poor), similar to those found in globular clusters. The empirical model for the disk assumed a broad range of stellar populations ranging from extreme Population I (hotter, younger, relatively metal rich) to Population II. The stellar luminosity functions and density scale heights were assumed to be fixed throughout the Galaxy; that is, they were not allowed to vary with distance from the Galactic Center. The functional forms for star density were derived from observed light distributions in external galaxies: The parameters included the scale height and length describing the exponential fall-off of the star density perpendicular to or along the Galactic Plane. Specific values for these parameters were determined from galactic observations, with the scale height allowed to vary with absolute magnitude, following observational trends (e.g., a larger scale height for disk dwarfs and a smaller one for disk giant stars). Similarly, the distribution of stars as a function of luminosity and their color-magnitude relations were determined for each of the two populations by fitting to local observations.

The model was then tuned by exploring small variations in the initial parameters to identify the values that could provide the best star counts and colors in various observational directions. This corrected for correlations among parameters that might not have been properly reflected in the initial values.

John and Ray made use of two observational data sets that were rapidly growing in the 1980s: the global large-scale properties of external galaxies—for instance, trends in luminosity as a function of distance from the Galactic Center or height above the disk midplane—and the local properties of our region of the Milky Way, including its luminosity density and metallicity. Their model provided a way to encode a great deal of observational data into a relatively small number of parameters and then to test the adequacy of the parameterization with further data.

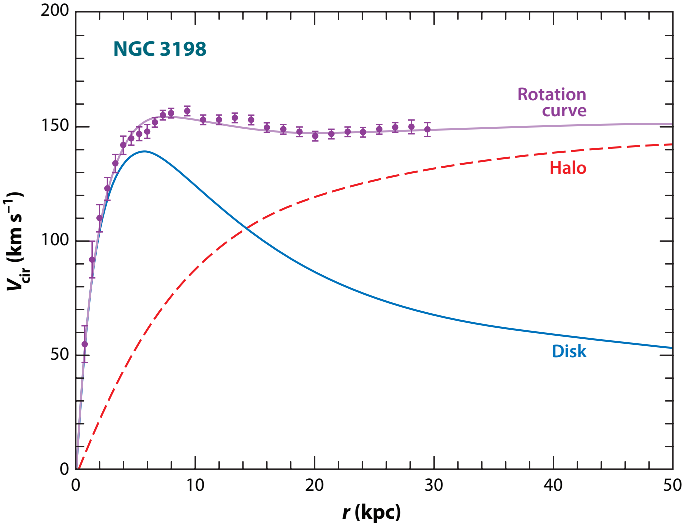

Figure 5

John Bahcall's work on the Bahcall–Soneira model of the Milky Way led him to consider halos in other galaxies. In his analysis of spiral galaxy NGC 3198, he concluded that the dark matter inside the last point of the rotation curve (at 30 kpc) exceeded the visible matter by at least a factor of four. Reproduced from Reference 73 with permission.

The model was used to test the consistency of star counts with predicted galactic properties. One of the first calculations done by John and Ray concerned the rotation curve predicted for the Milky Way: The disk and spheroid model fell monotonically beyond 12 kpc, whereas it was well known at the time that external galaxies of the same morphology had flat or slightly increasing rotational curves out to $\gtrsim$30 kpc (72). John and Ray showed that a massive halo component could be added to produce both the correct local rotational properties and a flat rotation curve out to distances in excess of 40 kpc and argued that if this component were stellar, it would have to be a new class of very faint stars that did not follow the star-count trends of known stars. This exercise sparked John's interest in evidence from rotation curves for dark matter in external galaxies and led to what today may still be the most dramatic observational example of this phenomenon (see **Figure 5**) (73). Because Oort (75) had argued that the amount of mass in the disk might exceed the amount observed in disk stars, John and Ray also used the model to place constraints on unidentified disk components. In work with Hut and Tremaine (74), John used the model's characterization of wide binaries to constrain any unobserved low-mass stellar population in the disk: Wide binaries can be disrupted by the nearby passage of such stars. John also investigated whether the disk might contain dark matter. His work on this subject spurred intense interest and controversy and led to the development of new analysis techniques that became widely used, although ultimately it turned out that his conclusions had been biased by an error in the distance scale that was not corrected until satellite observations became available in the 1990s.

The Bahcall–Soneira model served as a standard model for the Milky Way for two decades, and it remains in use today. By far the most successful and widely used descriptive model of the Milky Way, it forms a bridge between early observations and the far more detailed numerical models of the Milky Way that will be needed to interpret observations from the large-scale photometric, spectroscopic, and astrometric surveys of the coming decade. Ironically, John initially viewed his work on galaxy models mainly as a practice exercise for an equally ambitious model of the extragalactic universe, a task he never completed.

3.4. Compact Objects and Stars: The Bahcall–Wolf Cusp

Richard (Dick) Wolf, as a graduate student at Caltech, wrote a term paper for Willy Fowler's nuclear astrophysics course. Willy advised Dick to talk with John (then a postdoc, but soon to be an assistant professor at Caltech) about the paper and other topics. Dick became John's first student, and the term paper, on the termination of the proton-proton chain at high densities, led to Dick's first publication (76). In 1965, Dick completed his thesis on the rates of nuclear reactions in white dwarf stars and on neutron star cooling. Over a 12-year period, he and John collaborated on eight additional papers, including one describing the Bahcall–Wolf model for stellar clusters in the vicinity of a black hole (77).

Their work on neutron stars, occurring at the same time Bahcall and Davis were building their arguments for the chlorine experiment, was motivated by the possibility that neutron stars could be important galactic X-ray sources. The work focused on the early cooling of a hot neutron star by neutrino emission, including both the modified Urca process of Chiu & Salpeter (78),

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e,$$

and the effects of a possible pion condensate,

$$\pi^- + n \rightarrow n + e^- + \bar{\nu}_e.$$

Inclusion of the latter process—which they discovered could greatly increase the cooling rate of hot neutron stars—was remarkable, given that work on pion condensation in neutron stars did not begin until the early 1970s (79, 80). Sawyer and Scalapino note, in their first paper (80), that "[i]n almost all theoretical treatments the matter has been assumed to consist entirely of fermions, that is, baryons and leptons," but they modify this statement with a footnote to Bahcall and Wolf: "However, see J. Bahcall and R.A. Wolf. . .for a suggestion that pions may enter and for some of the consequences for neutron stars."

The two best-known papers by Bahcall and Wolf were on another topic, the distribution of stars around a massive black hole. This question was raised by Wyller (81) and then investigated semianalytically by Peebles (82, 83). In their first paper, Bahcall & Wolf (84) derived an evolution equation for the diffusion of stars in the $1/r$ potential of a black hole assuming: (*a*) a stellar distribution that is spherically symmetric in coordinate space, approximately isotropic in velocity space, and described by a one-body distribution, (*b*) stars of equal mass, (*c*) that the stellar mass is small compared to the black hole mass, which is small compared to the globular cluster mass, and (*d*) that a star is destroyed by star-star collisions or when its binding energy in the potential well exceeds a specified critical value. The resulting diffusion equation was solved numerically, showing that the stellar distribution function evolves rapidly to an equilibrium configuration on a timescale determined by the two-body gravitational relaxation time. The resulting equilibrium stellar density distribution around the black hole was found to vary as $r^{-7/4}$ (84). This result contradicted previous calculations, in which a variation of $r^{-9/4}$ had been found. Bahcall & Wolf showed that the error in earlier analyses arose from a subtlety in the boundary conditions near the black hole, which forced the flux of stars into the black hole to be throttled down nearly to zero. They argued that the characteristic density distribution of the Bahcall–Wolf cusp might allow one to identify black holes within nearby globular clusters, provided that the mass of the black hole $\gtrsim 5 \times 10^3\ \mathrm{M}_\odot$, or $\gtrsim 10^3\ \mathrm{M}_\odot$ given a large space telescope. In their second paper, they generalized the treatment to an arbitrary spectrum of stellar masses, finding similar results (85). In the case of a system of stars with two different masses, they found a shift in the power law index from

$\gamma = 7/4$ to $\gamma = m_1/4m_2 + 3/2$, with $m_1 < m_2$, suggesting that the sharpness of the cusp might vary from 3/2 to 7/4, depending on the breadth of the stellar mass distribution.

The initial motivation for the Bahcall–Wolf papers stemmed in part from the possibility that X-ray sources in globular clusters might be associated with a central black hole. It now appears that most or all such sources are due to individual stars. But the Bahcall–Wolf solution remains a topic of great interest because (*a*) high-resolution observations of the stellar populations in some globular clusters suggest that black holes may be present and (*b*) far more massive black holes are now known to reside at the centers of the Milky Way and other galaxies. In recent years, direct *n*-body simulations for stellar systems containing a massive central object have verified the time dependency (configuration space and phase space) predicted by the Fokker–Planck equation and have produced a Bahcall–Wolf density cusp with $\rho \propto r^{-7/4}$ (86). Observers have exploited the opportunity provided by our own Galaxy to study the structure and dynamics of stars in the vicinity of Sgr A*, the massive black hole at the center of the Milky Way. They have found some trends in agreement with the Bahcall–Wolf predictions, but also cusps with less severe slopes (87)—presumably because one of the assumptions of the Bahcall–Wolf analysis is not satisfied by Sgr A*.

3.5. High-Energy Neutrinos: The Waxman–Bahcall Bound

In the late 1990s, John became interested in a variety of questions concerning high-energy astrophysical neutrinos, including their sources, propagation, and connection with hadronic cosmic rays. One reason for his interest was the prospect that such neutrinos would soon be seen in a new generation of massive detectors. For example, IceCube, a high-energy neutrino telescope nearing completion in the Antarctic, uses strings of phototubes to view a cubic kilometer of deep, clear ice. Neutrinos may be the ultimate tool for probing the high-energy limits of the universe: They propagate over cosmological distances unimpeded by fields or matter.

In 1997, John began work in this area. He collaborated with Eli Waxman, who was completing a five-year research stay at the IAS. Among the papers produced by Eli and John were two concerned with defining the high-energy neutrino fluxes that might plausibly be produced in various astrophysical explosions. The upper limit they placed on such fluxes is known as the Waxman–Bahcall bound (88, 89).

The candidate astrophysical sources of very high energy neutrinos include objects such as active galactic nuclei (AGNs) and the fireballs responsible for gamma-ray bursts. The Waxman–Bahcall bound was based on arguments that the sources of high-energy neutrinos would also produce high-energy protons. The fluxes of hadronic cosmic rays are known for energies $\lesssim 10^{20}$ eV, the point at which their propagation is restricted by the cosmic microwave background. AGNs are likely sources of energetic protons because their powerful, extensive jets accelerate charged particles. These protons then produce high-energy neutrinos; sources include the decays of pions and kaons produced by photoproduction off protons, as well as proton-proton bremsstrahlung.

The Waxman–Bahcall bound applies to sources that are optically thin for high-energy protons with respect to meson-nucleon and photomeson interactions. With this assumption, one can relate the resulting neutrino flux produced by such sources to the corresponding high-energy cosmic ray proton flux because energetic protons can also leave the source. This is the basic idea behind the Waxman–Bahcall bound. From the observed flux of high-energy cosmic ray protons at Earth and the calculated fraction of energy lost by protons to pions, Eli and John derived the bound

$$E_\nu^2 \phi_\nu \lesssim 2 \times 10^{-8} \frac{\mathrm{GeV}}{\mathrm{cm^2\,s\,sr}}.$$

At the time the bound was published, more optimistic estimates of neutrino fluxes from AGNs and other sources were in the literature. Thus, this bound generated some discussion, a situation John

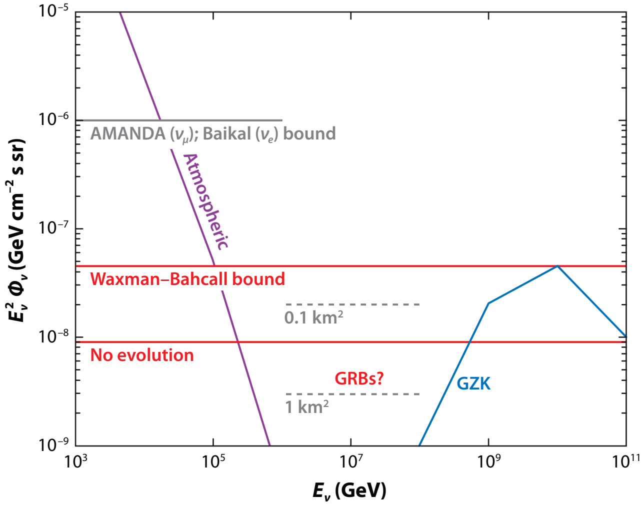

Figure 6

A viewgraph from John Bahcall's September 2000 talk at the International Conference on Neutrinos and Subterranean Science showing the implications of the Waxman–Bahcall bound for various neutrino telescopes.

generally relished. In terms of detector sensitivity, the bound converts to a minimum detector mass of about 0.1 gtons—if the bound is saturated. Thus neutrino telescopes such as IceCube (1 gton) may be sufficient to detect the very high energy neutrino flux (see **Figure 6**) (90).

4. REFLECTIONS AND ACKNOWLEDGMENTS

This attempted summary of John's scientific life is woefully inadequate. It is a one-dimensional projection of a career with many more dimensions. Those who knew John recognize that his impact goes far beyond the few selected topics described here. He was devoted to his work, with endless enthusiasm and energy for the problems he felt needed to be solved, and with a vision that often extended far beyond the present. But beyond this personal involvement in science, he had a very special gift for helping focus others on the important questions and for making his scientific goals a community destiny. Those of us who worked on the solar neutrino problem always knew that what we were doing was important—because it was important to John. I do not know how to express this other than to say—it does not feel the same now that he is gone.

On Saturday, October 29, 2005, the IAS hosted a Tribute to John Bahcall. I owe a great debt to the speakers who contributed to the Tribute's scientific session: Art McDonald, Carlos Peña-Garay, Eli Waxman, Buell Jannuzi, Scott Tremaine, Andy Gould, and Peter Goldreich. Their comments (91) inspired much of this prefatory article; I have stolen from them liberally. I am also indebted to Art Poskanzer and Dick Wolf for sharing their memories of John. Finally, I especially thank Neta Bahcall, Jim Peebles, and Scott Tremaine for reading, commenting on, and greatly improving this history. I am very grateful to Neta for her encouragement in this endeavor.

DISCLOSURE STATEMENT

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