Scientific memorial for John Bahcall

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Abstract. With the passing of John N. Bahcall in August, 2005, our field has lost a pioneer, innovator, mentor and friend. John has made many contributions to the fields of astrophysics and neutrino physics. In this memorial, I will primarily trace John's many contributions to neutrino physics and solar physics and indicate ways that he has displayed strong leadership during his extraordinary scientific career.

1. Introduction
John N. Bahcall, a leader of the fields of astrophysics and neutrino physics passed away on August 17, 2005, at the age of 70. Our field has lost a great scientist who led the development of solar models and encouraged and assisted a solar neutrino experimental program that has tested these models in great detail, providing fundamental information on the physics of the Sun and of neutrinos themselves.

Figure 1. John Norris Bahcall.
In this paper, I will concentrate on John's contributions to neutrino and solar physics, taking a historical timeline to emphasize not only John's theoretical contributions, but also the many ways in which he was responsible for the development of the field of solar neutrino physics itself. I am an experimental physicist and this account will be from that perspective. I know that his theoretical colleagues would give a much more detailed perspective of his theoretical contributions than is contained herein. John also made many contributions to other areas of astrophysics that I will not discuss in detail here, but will outline to show the breadth of his work.

John Norris Bahcall was born in Shreveport, Louisiana on December 30, 1934 and studied at the University of California, Berkeley (A.B., 1956), the University of Chicago (M.S., 1957) and Harvard University (Ph.D., 1961). He was a research Fellow at Indiana University and Caltech, and an Associate Professor of Physics at Caltech, before moving to the Institute for Advanced Study in Princeton, N.J. for the remainder of his career, becoming the Richard Black Professor of the Natural Sciences there in 1997. He also was a Visiting Lecturer with the rank of Professor at Princeton University from 1971 to 2005. John's wife, Neta Assaf Bahcall, is herself a noted astrophysicist and they have three children, Safi, Dan and Orli, all scientists.

John's many scientific contributions are given to us in over 500 scientific publications, books and presentations for the general public (for a compilation see his web page at the IAS: http://www.sns.ias.edu/~jnb/). The personal memories of his colleagues are dominated by observations of his intense love for science and his personal interactions and physics discussions with other scientists. John was one of the principal mentors of young theoretical astrophysicists for over forty years. He also loved to interact with experimental scientists. For many years he helped set directions for the field through his support for new experiments and new ideas. John was a very influential international scientist who used that influence for the benefit of the field, supporting the aspirations of individual groups and advising funding organizations on long term directions.

Those of us at this conference know John primarily because of his towering contributions to solar models, solar neutrinos, high energy neutrinos and the understanding of neutrino properties. Whereas I will concentrate on his contributions to the above topics, John has had a substantial impact on the whole field of astrophysics, including the following contributions:

1. The "standard model" for the galaxy, "the Bahcall-Soneira Model" has been the benchmark for models of the Milky Way. The standard model for a black hole surrounded by a cluster of stars is referred to as the "Bahcall-Wolf Model". John was one of the early vigorous advocates of the view that quasar redshifts are cosmological and his later Hubble Telescope observations strongly supported this view. He was one of the first to recognize that absorption lines from the intergalactic medium in the spectra of quasars provided an extremely powerful probe of the conditions at the onset of galaxy formation. He did important work on a wide variety of other subjects, including high energy neutrino sources, X-ray binary stars and global cluster dynamics. He also played a central role in lobbying for and planning the Hubble Space Telescope and chaired the 1990 Decadal Survey of astronomy that laid out plans for the ambitious set of new instruments that have been so successful since then.

2. During this period, John worked closely with Ray Davis in the establishment of the Homestake chlorine-based solar neutrino detector (see Figure 2). John was at Caltech, in Willy Fowler's laboratory and that was a very exciting place for nuclear astrophysics, as I remember from my graduate student days there in the latter part of this period. John worked on theoretical details of solar models, providing predictions of the fluxes of $^8$B and $^7$Be solar neutrinos. He also provided detailed calculations of the absorption cross sections for Cl, including an important calculation [1] that

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1 The compilation on the website is complete and well annotated, so only a few major references are used here.
2 I am grateful to S. Tremaine and J. Ostriker for consultation on this information.
included the isobaric analogue state and indicated a substantial increase in the sensitivity. This made a large difference in the potential experimental feasibility of the Homestake experiment. Following the initial measurements that showed a lower flux than expected, John participated extensively in further calculations and discussion of the results. He considered broadly all potential improvements to solar model calculations while also considering the possible impact of neutrino oscillation effects as discussed by Bruno Pontecorvo and his co-authors. During these years, John was an author on 28 papers relating to the sun and solar neutrinos.

Figure 2. Ray Davis and John Bahcall at the Homestake chlorine-based solar neutrino detector.

3. The years from 1969 to 1986
During this period, John and his theoretical collaborators worked extensively on refining the "Standard Solar Model", including the latest information available on opacity, nuclear cross sections and including other possible physical effects within the sun itself. As can be seen from Figure 3, the refinements did not result in any significant changes in the total predicted rates for detection by chlorine and the discrepancy between experiment and theory remained about a factor of three. He and his collaborators also considered carefully the many possible neutrino physics solutions to what had come to be known as the "Solar Neutrino Problem".

John was a tireless supporter of new experiments to help resolve the "SN Problem". In addition to papers calculating sensitivities for new experiments (including gallium, deuterium and indium), John was an enthusiastic consultant to experimenters and strong supporter in public forums. During the preparation of this talk I received strong testimonials from a number of experimenters such as R. Raghavan and V. Gavrin, who described the ways that John had been so helpful in the start-up of their experiments and in later years. The scientists of the SNO Collaboration are very grateful for the strong theoretical and other support provided by John throughout our experiment. From 1969 to 1986, John was an author on 55 papers relating to solar models, neutrinos and sensitivities of neutrino detection experiments.

4. The years from 1987 to 1995
The year 1987 was a very significant one for neutrino astrophysics with the observation of neutrinos from Supernova 1987a and the inclusion of the Mikheyev-Smirnov-Wolfenstein matter-interaction effect [2] in analyses of solar neutrino oscillations. John and his collaborators worked very quickly to study the neutrino signals observed from SN1987a (and other astronomical data) and relate them to the
properties of the supernova itself [3]. They also set limits on neutrino mass from the time dispersion of the signals that were close to the mass limits at that time from terrestrial experiments.

![Predicted rates for detecting solar neutrinos with $^{37}$Cl vs time.](image)

**Figure 3.** Predicted rates for detecting solar neutrinos with $^{37}$Cl vs time.

The MSW effect made a substantial difference in perspective for analyses of solar neutrino oscillations. It enabled significant oscillation effects even for relatively small mixing angles that were the theoretical expectation of the time. That was rather ironic, since the angle has now been determined to large, but it did increase the theoretical attention paid to oscillations as an answer to the low fluxes observed from the sun. Low observed fluxes, as obtained by the Homestake measurements were also seen by the Kamiokande experiment, using elastic scattering from electrons in light water, predominantly sensitive to electron neutrinos and providing directional sensitivity confirming the solar origin of the detected neutrinos. These results were followed a few years later by measurements with gallium radiochemical detectors that also showed fluxes lower than those calculated from solar models. The gallium measurements were also sensitive exclusively to electron neutrinos, and had substantial sensitivity to the lowest energy neutrinos from the pp reaction in the sun. Whereas these experiments all showed lower fluxes than calculated, they were sensitive to different combinations of solar neutrino reactions and showed somewhat different ratios of observed to calculated fluxes. John and Hans Bethe considered this carefully in a paper [4] where they showed that the observed fluxes could be explained by an energy dependence in the oscillation process (allowed by the MSW effect) and concluded that the explanation probably involved new neutrino physics.

John and his collaborators also worked extensively on improvements to solar models, including effects of diffusion and improved calculations of opacities and paid particular care in addressing all the reactions to which the neutrino experiments were sensitive. It this time span, John was an author on 64 papers in these areas, including 7 papers on SN1987a.

### 5. The years from 1996 to 2000

The availability of helioseismology data added strong new constraints for solar properties. John and his collaborators approached this topic in great detail in a number of papers and found quite remarkable agreement between the available data and their solar models, extending deep into the solar interior. Figure 4 shows the agreement as of the year 2000 from work with Pinsonneault and Basu [5]. There were no substantial changes indicated for the solar neutrino fluxes and the discrepancies with experiment remained. As can be seen from the arrow in the figure, these results placed strong constraints on possible changes in solar neutrino fluxes that might improve agreement with experiment, such as reduction of the flux of $^7$Be neutrinos.
All of the existing solar neutrino experiments (Cl, H\textsubscript{2}O, Ga) continued to operate and improved their accuracy steadily. The beautiful data for the disappearance of atmospheric neutrinos obtained by Super-Kamiokande that was best fit with the oscillation of massive neutrinos, lent credence to such oscillations (coupled with the MSW effect) as an explanation for the observed measurements for solar neutrinos. However, searches for solar-model-independent effects such as distortion of the energy spectrum observed by Super-Kamiokande and day/night or seasonal variations in fluxes did not provide clear evidence for solar neutrino oscillation. John and his collaborators were centrally involved in understanding all possible particle physics explanations to the solar neutrino data. Figure 5 shows the status of allowed regions of mass and mixing angle for the oscillation of massive neutrinos, including MSW effects, for active and sterile neutrinos, as calculated in reference [6].

6. The years from 2001 to 2005
In 2001 and 2002, the SNO collaboration published [8] solar neutrino "appearance" measurements with D\textsubscript{2}O that showed clear evidence for solar neutrino flavour change. In these results, the hypothesis of no neutrino flavour change was ruled out by 3.3 standard deviations by comparing SNO and Super-Kamiokande data and then by 5.3 standard deviations by comparing two reactions on deuterium, one sensitive to only electron neutrinos and the other sensitive equally to all neutrino types. The conclusion of flavour change did not depend on detailed solar model calculations to specify the fluxes from different reactions since only \textsuperscript{8}B neutrinos were involved. The measurements indicated that about two-thirds of the \textsuperscript{8}B electron neutrinos had changed to other types before reaching the earth and thereby showed an initial flux of \textsuperscript{8}B electron neutrinos in excellent agreement with solar model calculations. John Bahcall greeted these measurements with great enthusiasm, as can be seen from a quotation in the New York Times:

Dr. Bahcall was ecstatic. "I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty," Dr. Bahcall said. "For 33 years, people have called into question my calculations on the Sun." The new finding "shows the calculations were correct," he said. "I feel like dancing," he added.
John's enthusiasm was again high when the results from Kamland showed disappearance of reactor anti-neutrinos for oscillation parameters that overlapped the acceptable (Large Mixing Angle) solar neutrino oscillation region. The overall confirmation of the solar models with great accuracy is indeed a tribute to John's scientific perseverance and the uncompromising quality of his work. Our current knowledge of the sun and of neutrino properties would not have been possible without the tremendous efforts that John made over many years to understand the science in great detail. We are all in his debt for this work, for the strong leadership he showed and for his mentoring of generations of young scientists who are now leaders in the field.

During 2001 to 2005, John was an author on 28 papers that explored the acceptable regions of neutrino masses and mixing parameters that fit the full set of available data, as well as extending solar model calculations and considering other non-dominant processes beyond the oscillation of massive neutrinos. In characteristic fashion, he also considered the impact of the available data on other future experiments such as double beta decay and future solar neutrino measurements. He was a strong supporter of future underground laboratories to house such experiments. He continued his work on solar models, including new information on helioseismology and solar abundances. Even during his final illness, John continued his active research and in his last year he provided 9 articles on solar neutrinos as well as several articles in the popular press in support of the Hubble Space Telescope program.

7. Awards, Recognitions and Community Service
John Bahcall received many awards during his career and he provided broad service to the community in addition to his research work. He served as President of the American Astronomical Society and would have been President of the American Physical Society in 2006. He chaired many committees in the fields of astronomy and physics and for the U.S. National Academy of Science (of which he and Neta are both members). John received many prestigious prizes and awards, including the Dannie Heinemann Prize, Hans Bethe Prize, National Medal of Science, Russell Prize, Bernhard medal, Benjamin Franklin Medal, Dan David Prize, Gold Medal of the Royal Astronomical Society, Fermi Award, Comstock Prizem six Honorary degrees and the NASA Exceptional Scientific Achievement Medal (awarded posthumously).

8. Conclusion
John Bahcall was a leader, visionary and mentor. He had a great love for science, an insatiable curiosity and boundless enthusiasm and energy. He was an influential scientist who used that influence
for the benefit of scientific research and was a loving family man. I will close with a quote that John liked very much and included in his presentation at the Neutrino 2000 conference in Sudbury. It is from T.S. Eliot, Four Quartets (1943):

We shall not cease from exploration  
And the end of all our exploring  
Will be to arrive where we started  
And to know the place for the first time.

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